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SHIP POWER PLANT SELECTION

Wesley Charles Hewitt

SHIP POWER PLANT SELECTION

by

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SUBMITTED IN PARTIAL FULFILLMENT OF THE

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Thesis
H52625

SHIP POWER PLANT SELECTION

by

WESLEY CHARLES HEWITT

Submitted to the Department of Ocean Engineering and Department of Mechanical Engineering on 2 June 1972, in partial fulfillment of the requirements for the degree of Ocean Engineer and the degree of Master of Science in Mechanical Engineering.

ABSTRACT

Ship power plant selection is undertaken in a rational manner including consideration of the following:

- owner requirements
- propeller selection
- propeller-ship and propeller-prime mover matching
- economic and qualitative factors of the problem related to steam, diesel and gas turbine power plants

The selection problem is simplified for preliminary analysis. Next it is organized and summary tables for the overall problem and for the cost calculations are developed.

A literature survey was conducted to develop cost data for the initial and operating costs of steam, diesel and gas turbine power plants. The cost data and amplifying information are in the appendices indexed for the elements in the cost summary table.

A representative ship was selected and the methodology, information and data in the thesis was used to develop evaluation factors for the power plant selection study. The result of the study indicated that the process lead to reasonable evaluation factors and that superior or very poor plants could be identified early in the ship design iterative spiral.

Thesis Supervisor: A Douglas Carmichael
Title: Professor of Power Engineering

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NOMENCLATURE

%	= percent
$	= dollar U.S.
bbl	= barrel
C_B	= block coefficient
C_d	= coefficient of resistance
C_f	= coefficient of frictional resistance
C_m	= midship coefficient
C_p	= prismatic coefficient
CRF	= capital recovery factor
C_t	= total coefficient of resistance
D	= diameter
EHP	= effective horsepower or tow horsepower
ESC	= external ship characteristics
gal.	= gallon
hr.	= hour
i	= interest rate per year
J	= propeller advance coefficient
JP-5	= Navy distillate aircraft fuel
K_Q	= torque coefficient or open water torque coefficient
$(KQ)_{sp}$	= self propelled torque coefficient
K_T	= thrust coefficient
lbs.	= pounds
LCC	= life cycle cost
n	= revolutions per second
N	= number of interest years
P	= pitch
PC	= η_p = propulsion coefficient
PW	= present worth
Q	= torque
Q_{SP}	= torque self propelled
R	= resistance
RPM	= revolutions per minute
s	= slip ratio
s*	= true slip ratio
S	= wetted surface area
sec	= second
SFP	= shaft horsepower
t	= thrust deduction factor
T	= thrust
V	= velocity (or speed)
V_A	= velocity the propeller works in
W	= wake fraction
yr.	= year
η_{HULL}	= hull efficiency
η_p	= PC = Overall propulsion efficiency
η_{PI}	= ideal propeller efficiency
η_{PC}	= open water propeller efficiency
η_{PO}^{MAX}	= maximum open water propeller efficiency

NOMENCLATURE

η_r	=	relative rotative efficiency
η_{SHAFT}	=	transmission efficiency
ΔC_f	=	roughness factor
Δ	=	change of
Δ	=	displacement
∇	=	displaced volume
ρ	=	density of water
π	=	3.14...
R	=	Reynolds Number
F	=	Froude Number

1. INTRODUCTION

Ship power plant selection is an intricate problem involving many requirements and considerations. The requirements include ship speed, endurance and schedule. Primary consideration is given to the ship, its prime mover and propeller. These three completely different physical machines working together influence the economics of the whole problem. Other considerations involve quantitative and qualitative factors, with their various degrees of subdivision, which contribute to the understanding and the analysis of the problem.

Who is responsible for selection of the power plant? This question is answered by Gillmer in his book, Modern Ship Design. [1] He states:

> "... It cannot be emphasized too strongly that the selection... of the proper propelling machinery is in the province of the naval architect."

In this thesis, the ship power plants and their respective prime movers refer to conventional steam, diesel and gas turbine plants. The propellers considered are fixed blade but the discussion is applicable to controllable-reversible pitch propellers. The prime movers and the propeller shafts are connected either directly or through gearing; these modes of coupling are called direct drive and geared drive respectively.

Organization of the thesis is as follows:

First, to discuss the characteristics of the ship, its propeller and prime mover, and the influence these characteristics have on the propulstion efficiency (or propulsion coefficient). The primary input into the economics of the selection problem is based on the prime mover's shaft

horsepower. Therefore, the importance of the propulsion coefficient is stressed since the prime mover's shaft horsepower rating is dependent upon it.

Secondly, to select pertinent factors from the general problem which when analyzed will contribute to evaluation of the power plants. The evaluation factors are composites of the quantitative and qualitative elements of the simplified problem.

Thirdly, to illustrate the selection procedure a representative problem is summarized. The economic and subjective factors of the problem are both considered and evaluated.

Fourth, and finally, to discuss the conclusion drawn from the representative problem and the thesis overall.

2. THE SHIP PROPULSION SYSTEM

A ship power plant has many functions to perform with the power it derives from its fuel. These functions include powering the ship's propeller(s), generating electrical power, distilling water, providing air conditioning, ventilation and other hotel and support services. Although these auxiliary power levels are sometimes high (cargo pumping for tankers) they will be neglected in this study.

The governing requirement for conventional steam, diesel and gas turbine ship power plants is the requirement to propel the ship at its design speed for a required length of time. The system for propelling the ship is called the propulsion system, which includes the prime mover, reduction gear (if needed), and propeller. For preliminary analysis the power plant's weight, its initial and operating costs all may be correlated to the propulsion system type and its continuous shaft horsepower rating.

Based on the power plant's propulsion requirement and other owner requirements, such as weight and/or volume of payload, the naval architect is able to determine a suitable hull shape and the resistance of that hull at the design speed.

A block diagram showing the essential steps for calculating ship resistance is shown in Figure 2.1. The ship resistance, R,

$$R = C_t \tfrac{1}{2} \rho V^2 S \qquad (1)$$

S is the wetted surface area of the ship's hull, ρ is the density of sea water, V is ship speed and C_t is the total resistance coefficient. The theoretical analysis and methodology for determining ship resistance is available in standard naval architecture texts and reference books, including

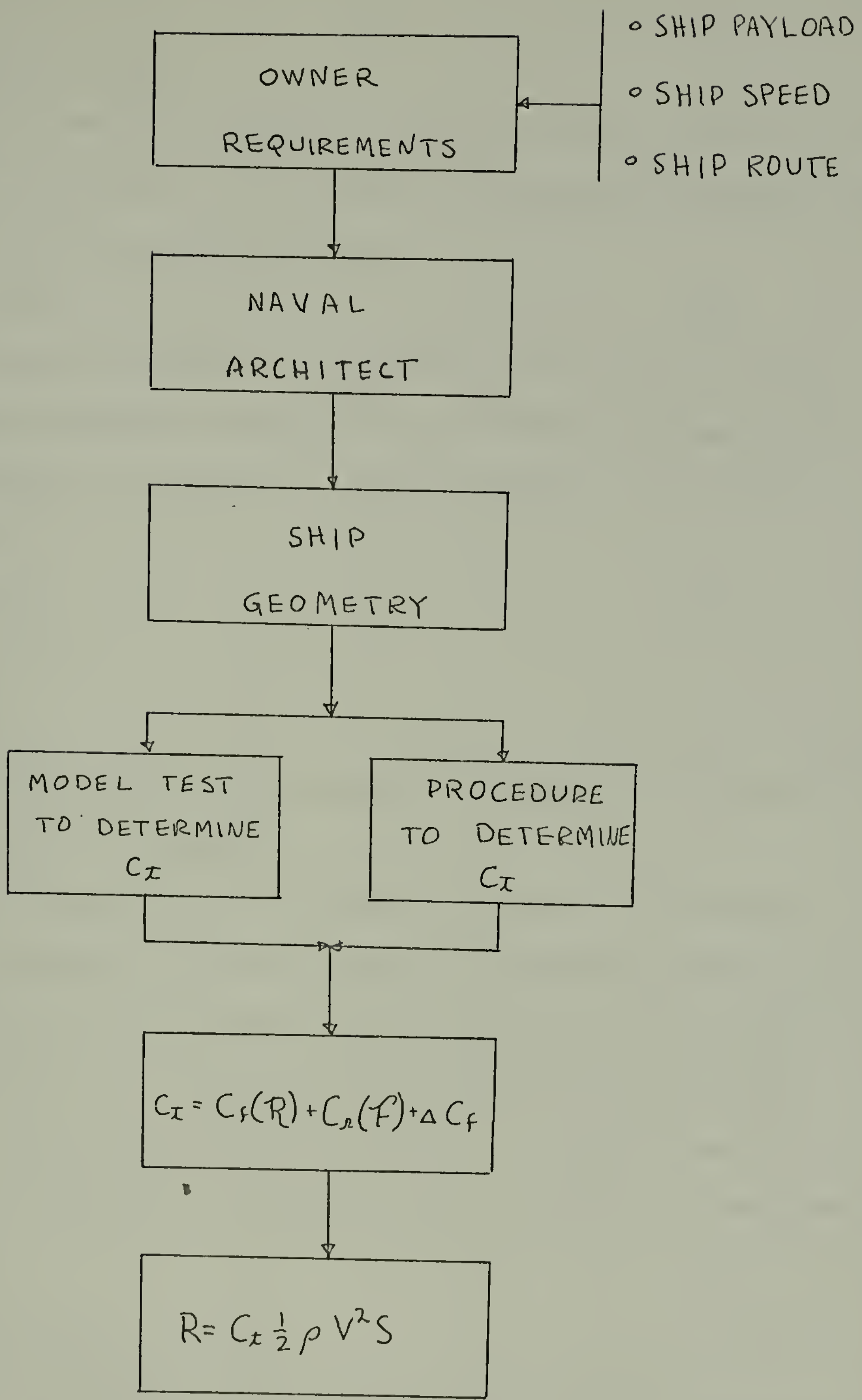

Figure 2.1 BLOCK DIAGRAM SHIP RESISTANCE DETERMINATION

references [1], [2] and [3].

From the resistance the horsepower to propel the ship hull at the design speed and displacement is determined. The resulting horsepower is defined as the design effective horsepower,

$$EHP = R \cdot V/352.6 \qquad (2)$$

where R is in pounds force and V is in knots (nautical miles per hour).

The power to the ship's propeller(s) is the shaft horsepower (SHP). The ratio of effective horsepower to shaft horsepower is the propulsion coefficient, PC.

$$PC = EHP/SHP \qquad (3)$$

rewriting equation 3.

$$SHP = EHP/PC$$

Since at the design speed and displacement EHP is fixed it is obvious that the shaft horsepower is dependent on PC.

The propulsion coefficient is primarily dependenton the propeller efficiency. The propeller efficiency in turn is influenced by interaction with the ship's hull and the RPM at which it is driven by the propulsion system prime mover. The propeller selection process requires an understanding of propeller characteristics, propeller-to-ship interaction factors, as well as consideration for matching the prime mover to the propeller.

2.1 Matching Propeller to Ship Hull

Appendix A. provides a review of the propeller and its characteristics and the matching of these characteristics with the characteristics of the ship hull. The equation

$$D^2 \frac{K_T}{J^2} = \frac{EHP}{V^3} \frac{550}{\rho\ (1-w)^2\ (1-t)} = ESC \qquad (4)$$

is the important relation between the propeller characteristics (D, K_T and J) and the external ship characteristics (ESC). The usefulness of this relation is increased since in the speed ranges of interest ESC may be considered constant. This allows

K_T = (constant) (J^2)

where the constant represents the external ship characteristics which then may be plotted on the K_T, η_{p0}, J propeller chart. See Figure A.8. The result is that a maximum propulsion coefficient which includes consideration of the external hull characteristics may be determined. The maximum propulsion coefficient also establishes a corresponding optimum propeller RPM. See Appendix A, paragraph 9, for a sample propulsion coefficient and RPM calculation.

2.2 Matching Prime Mover and Propeller [4, 5, 6, etc.]

The published literature does not have many articles on the subject of matching propeller and prime mover. Woodward in reference [6] states the following:

> "It is no overstatement to say much has been written about the marine propeller. Essentially, none of this literature, however, treats the behavior of the propeller as a load for the engine that turns it, nor discusses the interactions of the propeller characteristics and engine characteristics. The standard textbooks in naval architecture and marine engineering...are totally silent on these topics, and during twenty odd years of surveillance of marine engineering literature,

only a handful...of exceptions have appeared."

The reason for this apparent deficiency might be the determination of the power plant by the ship designer before the marine engineer's expertise is integrated into the ship design.

2.2.1 Prime Mover and Prime Mover-Propeller Connection [4, 7, etc.]

The power to turn the propeller shaft with its attached propeller is developed in the propulsion system prime mover. The prime mover may be a steam turbine, a diesel engine or a gas turbine. Each prime mover has its own operating characteristics as well as its own advantages and disadvantages. The operating characteristics are briefly discussed in the following paragraph.

The propellers considered are fixed pitch and may have varying numbers of blades. The propeller is attached to a shaft which may be connected directly to the prime mover or connected to it through gearing. The method of connection will depend upon the prime mover's speed of rotation. Direct coupling is used for low-speed diesels which operate at about 100 RPM. Single reduction of the RPM is used for medium-speed diesels which operate at about 450 RPM. And double reduction gear boxes are used for steam and gas turbines which operate in the range 2500 to 6000 RPM. For direct drive the prime mover operates at the same RPM as the propeller while for geared drive the prime mover and propeller operate at different RPM's which has the advantage of operating with the increased propeller efficiency at lower RPM's.

2.2.2 Prime Mover Characteristics [4, 6, 8, 9, 10, 11, 12, 13, etc.]

The operating characteristics in common between the prime

mover and the propeller are torque, power and revolutions per unit time. As stated above each of the conventional prime mover types have different operating characteristics; for discussion, only shaft horsepower and RPM will be considered. Figure 2.2 shows representative horsepower-RPM characteristics for various power plant types together with a propeller characteristic.

The prime mover and the propeller obviously have only one operating point at a throttle setting, and that point is where these characteristics cross. For a gas turbine the maximum power developed is a strong function of the inlet ambient temperature and high temperatures reduce the available power.

The various RPM ranges of the prime movers were discussed earlier.

2.2.3 Matching Problems [4, 5, 6, etc.]

As seen in Figure 2.3 for a specific RPM there is only one operating point common to both the power plant prime mover and the propeller at the maximum continuous power level. As discussed earlier matching the propeller with the ship hull established the maximum propulsion coefficient and its corresponding RPM.

The direct coupling between the diesel prime mover and propeller shaft creates the obvious matching problem, the solution of which is iterative. Usually the best economic solution is to pitch the propeller to match the RPM at which the prime mover develops its continuous rated horsepower.[5, 6]

Other propeller-prime mover matching problems result from the manufacturer's off-the-shelf components not being the power rating or the RPM

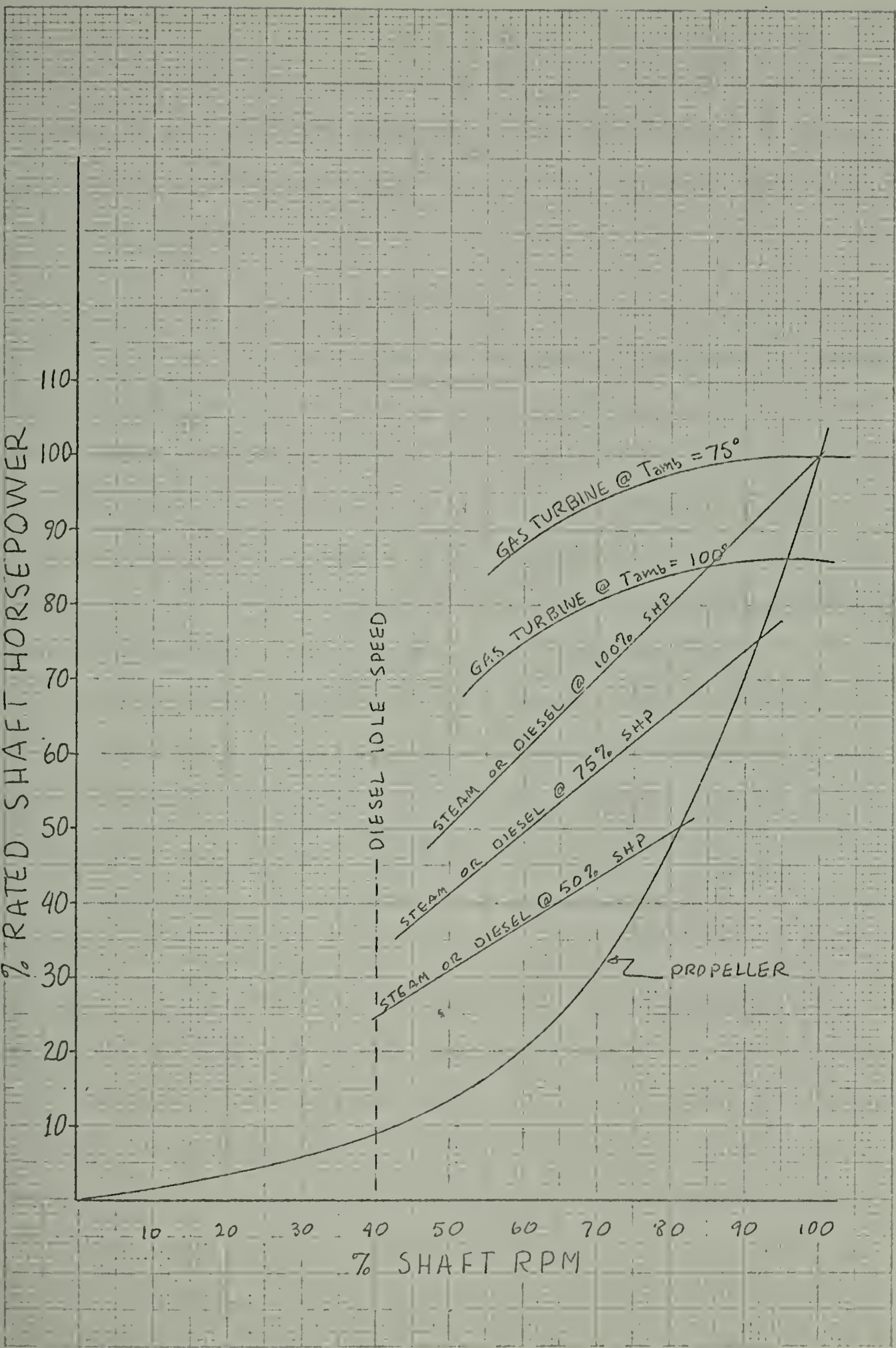

Figure 2.2 TYPICAL POWER PLANT PRIME MOVER AND PROPELLER SHP-RPM CHARACTERISTICS [4, 8, 12, 13]

needed. The power plant prime movers come in various but incremental ranges such as 1200 HP per diesel engine cylinder or 25,000 HP per gas turbine, etc. The reduction gears also are in incremental gear ratios as well as horsepower ratings.

2.2.4 Other Matching Considerations [4, 5, 6, 9, 14, 15, 16, etc.]

The design point problem was generally discussed in paragraph 2.2.2. Another consideration which may have significant affect on the choice of power plant is the allowance in prime mover for the change in propeller horsepower owing to increased hull resistance with time out of drydock, ship loading and age of ship. The effect of increased hull resistance is illustrated by curve "A" in Figure 2.3. Propeller curve "B" represents decreased hull resistance due to light shipload.

The ship mission operating profile should also be considered. The speed ranges the ship might operate at other than the design speed may cause significant economic and effectiveness changes. Combined plants which cruise using the diesel plant and use gas turbine either with or instead of the diesel for boost power (or high speed) result from this type analysis.

Both the gas turbine and the diesel have two rating definitions that may affect the SHP. Gas turbine prime movers are rated at about 10-12% above their continuous recommended operating power [9, 14], while diesel prime movers are rated about 15% above their continuous recommended operating power.[15] For power plant the continuous rating should be used.

Steam plants tend to be designed at the level at which it can be operated continuously, plus a small tolerance to allow for manufacturing

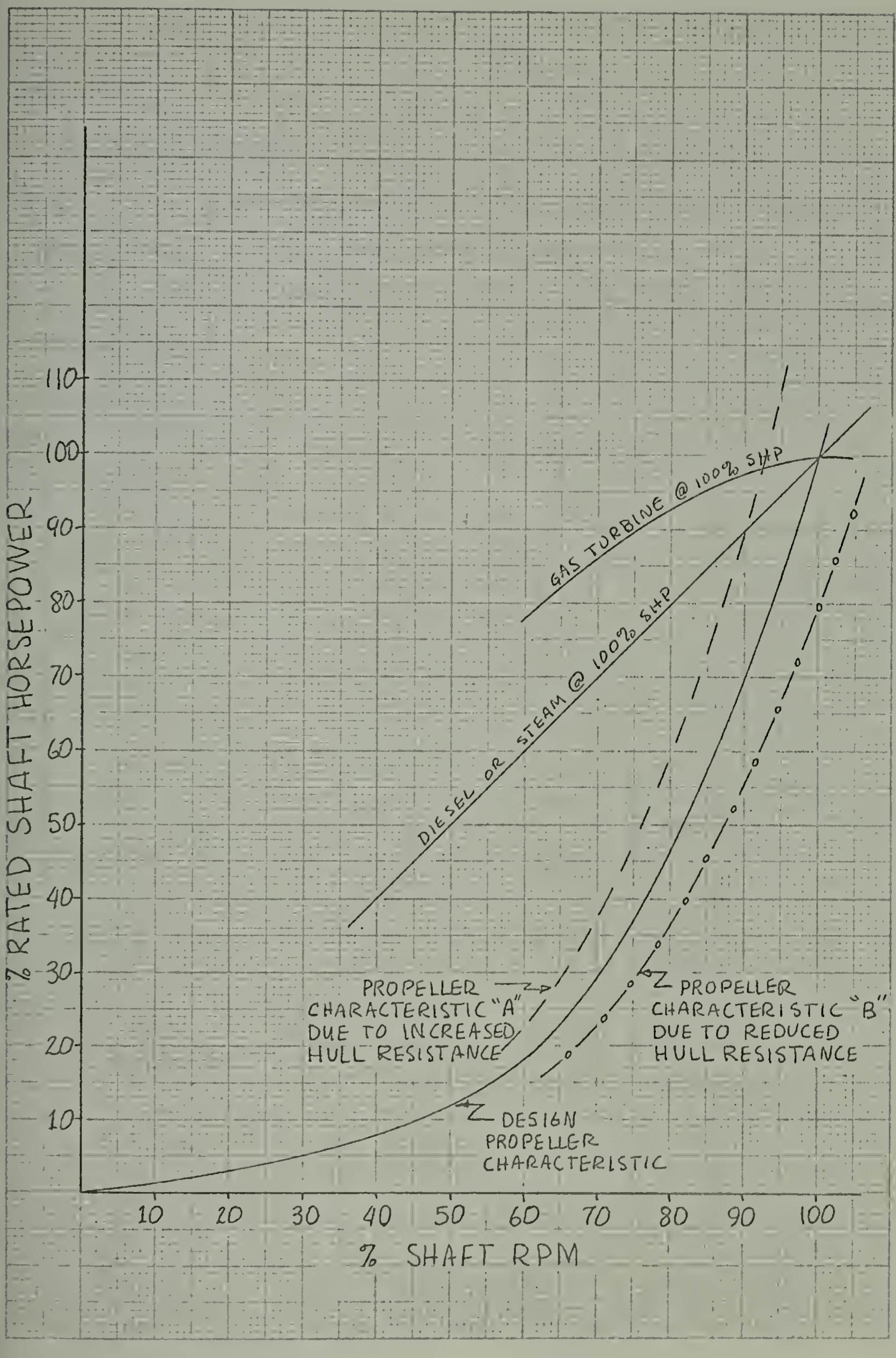

Figure 2.3 TYPICAL PORPELLER SHP-RPM CHARACTERISTICS FOR DESIGN, INCREASED AND DECREASED HULL RESISTANCE [2, 4, 6]

margin.[16]

Disregarding the small mismatch caused by incremental gear ratios available in off-the-shelf reduction gears leaves only the direct-drive diesel with significant mismatch probability.

For additional information about prime mover-propeller matching see reference [5].

3. SHIP POWER PLANT EVALUATION

The ship power plant evaluation procedure presented here will be based on comparison of life cycle cost and a figure of merit(sometimes referred to as effectiveness) of the power plants considered. Definition of the selection problem, its organization and information for determining the life cycle cost and figure of merit are presented in this section.

3.1 Defining the Power Plant Selection Problem

A detailed power plant evaluation may require consideration of more than one hundred inputs into the problem. In Table 2, "Power Plant General Requirements and Considerations," of reference [18] more than one hundred and twenty such factors are identified. To consider all factors of the selection problem would require analysis beyond the scope of this thesis. Simplifying the problem by a judicious choice of essential factors reduces the problem to manageable proportions.

The basic power plant choices have been discussed in the previous chapter. The next step is to consider the economic and related inputs. In order to provide a meaningful selection procedure it is necessary to consider the following factors:

- Effective Horsepower (EHP)
- Propulsion Coefficient (PC)
- Shaft Horsepower (SHP)
- Ship Trip, Miles Between Refuelings
- Ship Speed
- Operating Days per Year

- Initial Power Plant Cost
- Annual Operating Cost
- Life Cycle Cost
- Safety
- Reliability
- Maintainability
- Quietness
- Figure of Merit

3.2 Organizing the Problem

The selection problem may be divided into four major parts. This first part includes those factors necessary to calculate the initial and operating costs of the power plants. The second includes those factors upon which life cycle cost is based. The third part includes those factors which have been chosen to base figure of merit. And the fourth part is the power plant evaluation factors, life cycle cost and figure of merit.

These parts of the selection problem and their respective factors may be combined with the characteristics of the various power plants to form a summary table. Figure 3.1 shows how such a summary table permits organization of this data into an orderly array.

Entries for the summary table are discussed in the following paragraphs.

3.2.1 Part One Entries, Ship and Propulsion System Requirements

The prospective ship owner establishes the ship mission, defined in terms of ship purpose, schedule and payload. These requirements provide the starting point for the power plant selection analysis. Part one entries

POWER PLANT TYPE		STEAM	LOW SPEED DIESEL	AIRCRAFT DERIVATIVE GAS TURBINE	STEAM	ETC.
NO. OF PROPELLERS		ONE	ONE	ONE	TWO	
PART NO.	PROBLEM FACTORS					
ONE	EHP/PC/SHP					
	TRIP MILES/SPEED					
	OPERATIONAL DAYS PER YEAR					
TWO	LIFE CYCLE YEARS / ANNUAL INTEREST RATE					
	INITIAL COST					
	PRESENT WORTH OPERATING COST					
THREE	SAFETY					
	RELIABILITY					
	MAINTAINABILITY					
	QUIETNESS					
FOUR	FIGURE OF MERIT					
	LIFE CYCLE COST					

Figure 3.1 FORMAT FOR POWER PLANT SUMMARY

are determined from these requirements. Comments on each entry are listed below along with their problem factor, as defined in Figure 3.1.

Part One Problem Factor	Comment
EHP	Determined from owner requirements by a naval architect. See Chapter 2.
PC	Determined by engineering analysis to maximize propulsion coefficient, PC, by matching the ship's propeller(s) with the ship hull and propulsion system prime mover. See Chapter 2 and Appendix A.
SHP	Calculated by dividing EHP by PC.
Trip Miles	Determined from owner requirements and is based on miles between refuelings.
Ship Speed	Determined from owner requirements.
Operating Days per Year	Determined from owner requirements.

3.2.2 Part Two Entries, Cost Data

Calculation of life cycle cost is based on the Part Two Entries. The annual interest rate entry is based on current interest rate for a loan to finance the construction and initial operation of a ship. Ship life cycle and period of loan are assumed to be twenty-five years. The initial and operating costs are determined using information in paragraph 3.3 and information and data in the appropriate appendices.

3.2.3 Part Three Entries, Qualitative Factors

Safety, reliability, maintainability and quietness have been

selected as being most important to the general power plant selection problem. These qualitative factors of the selection problem are discussed in paragraph 3.4.

The figure of merit entries for these factors are generated using a procedure which considers both the factor and its priority. A sample figure of merit calculation is also worked out in paragraph 3.4.

3.2.4 Part Four Entries, Evaluation Factors

Calculation of life cycle cost using two different methods is outlined in paragraph 3.5. Both of these methods are numerical calculations dependent upon initial and operating costs of the various power plant types. One of the methods incorporates life cycle years and annual interest rate while the other incorporates loan period and annual interest rate. The calculated life cycle cost becomes one entry for Part Four.

The second entry for Part Four is figure of merit. Figure of merit is the total of the Part Three Entries for each power plant type.

3.3 Initial and Operating Costs

Calculation of the ship power plant initial and operating costs requires further subdivision of these two problem factors into cost elements. The degree of subdivision of these factors or the number of cost elements will depend on the scope of the analysis. For preliminary analysis the cost calculation problem will include the following:

- Power Plant and Installation Cost
- Hull and Structure Cost due to Manning
- Hull and Structure Cost due to Change in Fuel Rate and Power Plant Weight

- Support Equipment and Installation Cost
- Annual Maintenance and Repair Cost
- Annual Manning Cost
- Annual Outage Cost due to Breakdowns and Reduced Power at Sea and Delays in Port
- Annual Fuel Cost
- Annual Lube Oil Cost
- Annual Support Equipment Operating Cost

Methods of calculating these costs were derived from published data and are presented in Appendices B through K.

3.3.1 Cost Summary Table

The above listed initial and operating costs may be combined with the various power plant types to form a cost summary table format. See Figure 3.2.

3.3.2 Cost Summary Table Entries

The entries for the cost summary table, as stated earlier, are based on information and data in the appendices. Figure 3.2 with appendix designation also becomes the index for entering the appendices.

Sample initial and operating cost calculations where considered appropriate have been worked out in the respective appendices.

3.4 Qualitative Factors of the Problem

As stated earlier, safety, reliability, maintainability and quietness have been selected as being important to the general power plant selection problem. For preliminary analysis these factors will not be further

TYPE OF COST	POWER PLANT TYPE NO. OF PROPELLERS	STEAM	LOW SPEED DIESEL ONE	AIRCRAFT DERIVATIVE GAS TURBINE ONE	} ETC.	REFERENCED APPENDIX OR CHAPTER
INITIAL	POWER PLANT ACQUISITION AND INSTALLATION COST					B
	HULL AND STRUCTURE COST DUE TO MANNING					C
	HULL AND STRUCTURE COST DUE TO CHANGE IN FUEL RATE AND POWER PLANT WEIGHT					D
	SUPPORT EQUIPMENT ACQUISITION COST					E
	TOTAL					
OPERATING	MAINTENANCE AND REPAIR COST					F
	MANNING COST					G
	OUTAGE COST					H
	FUEL COST					I
	LUBE OIL COST					J
	SUPPORT EQUIPMENT COST					K
	TOTAL					
	PRESENT WORTH FACTOR					SEE CH. 3
	PRESENT WORTH OPERATING COST					SEE CH. 3

Figure 3.2 FORMAT FOR COST SUMMARY AND COST CALCULATION INDEX

subdivided.

The figure of merit for each power plant type will be the sum of the individual merits of each factor. Before considering assignment of a merit value to each factor they will be discussed briefly in the following paragraphs.

3.4.1 Safety [15, 16, 18, 19, etc.]

The safety factor includes consideration for the ship's crew, the ship itself and the ship's cargo. Two areas of concern regarding safety which are discussed in most articles and reports that compare various power plant types are hazards due to power plant fires and hazards due to collisions and groundings. The latter hazard area is linked to the power plant by considering reversing power to stop the ship, time to reverse the thrust, etc.

Fuel processing systems and use of more volatile marine distillate fuels make those plants that use them potentially more hazardous. In reference [16] it states:

> "An examination of marine casualty records over a period of several recent years discloses that, generally speaking, engine room fires are more prevalent on diesel powered ships than on steam ships."

The fire hazard problem should be given greater consideration for a tanker or flammable bulk liquid carrier.

The U. S. Maritime Administration requires that astern (or backing power) be at least 40% of the continuous rated ahead power. The ability to stop and back the ship are important considerations that affect that ship's ability to avoid collisions and groundings.

The time from complete shutdown to the time to provide 50% and 100% power are considerations for ship safety. A grounding resulting from a storm sweeping an anchored or moored ship into the rocks may have been prevented if a lengthy light-off and warm-up period for the power plant were not required.

3.4.2 Reliability [14, 20, 21, etc.]

How reliable a ship is in performing its mission is directly related to the reliability of its power plant. The reliability of the power plant is related to the degree of trouble-free operation of the various components and systems of which it is made up and the ability to continue operation if a casualty or failure to one or more of them occurs.

The reliability of a power plant is influenced by the following:

- Type of prime mover
- Redundancy of equipment and systems
- Selection of proven components
- Age of the power plant
- Quality of the personnel who operate, maintain and repair it
- Etc.

3.4.3 Maintainability [7, 14, 16, 18, 19, 21, 22, etc.]

The ability to maintain and to conduct preventive maintenance on the power plant to insure a high degree of reliability is the general concept of maintainability. Accessibility, complexity, degree of automation, skill requirements, and availability of spare parts are but a few of the many considerations given to maintainability. The time to accomplish

maintenance and whether the equipment requires complete shutdown or not also contribute to its maintainability.

The maintenance requirements for the steam, diesel and gas turbine plants are all different. Steam plants as a general rule require less maintenance than diesel plants; some attribute this to the fact that the steam plants have fewer moving parts.[22] Gas turbine prime movers all may be more readily interchanged than either the steam or diesel plant prime movers. Many maintenance and preventive maintenance tasks may be conducted on the operating steam plant. To accomplish comparable tasks on the diesel and gas turbine plants requires complete shutdown, etc.

3.4.4 Quietness [7, 18, 21, 22, 23, etc.]

Quietness of a ship power plant is related to the structural and airborne noise generated by it. The noise is produced from the vibrations generated by the prime mover and the processes of fuel combustion, as well as the propeller shafting, reduction gears if installed, inlet air, exhaust gases, etc.

The noise and vibration levels are important because of the man-machine interfaces. The noise and vibration tolerance for a man must be considered along with the possible damage to the ship's structure and the machinery itself.

Generally steam plants are the most quiet. Both diesel and gas turbine plant installations consider placing the prime movers in sound isolated spaces or having sound proofed operating booths for the operators. Vibrations from the steam and gas turbine plants are much less than a comparable diesel plant which usually requires considerable reinforcement in the power plant foundations.

3.4.5 Sample Figure of Merit Calcultion [17]

Figure of merit values for Part Three Entries are derived using a procedure adopted from reference [17]. This procedure is best illustrated by referring to Figure 3.3 and following the outline given below.

Figure 3.3 is divided into two sections. The upper or auxiliary section is used to rank the power plants for each factor considered and then to rank the factor itself. The entries for Part Three of Figure 3.1 are obtained by multiplying the merit values assigned to these two rankings. The lower section of the figure represents Part Three of Figure 3.1.

The values are qualitative and represent the experience and prejudice of the writer. These numbers may of course be modified as required.

Auxiliary Section

	Steam	Slow Speed Diesel	Aircraft Gas Turbine	Factor Priority Rank Value
	Power Plant Rank Value			
Safety	5	6	9	10
Reliability	9	8	8	8
Maintainability	8	6	9	7
Quietness	9	4	5	5
Part Three Entries				
Safety	50	60	90	
Reliability	72	64	64	
Maintainability	56	42	63	
Quietness	45	20	25	
Figure of Merit:	223	186	242	

Figure 3.3 SAMPLE FIGURE OF MERIT CALCULATION

The procedure is as follows:

Step One: For each factor of Part Three compare the various power plant types and assign a rank value from 0 to 10 based on their known or judged merit.

Step Two: Now consider the factors themselves and assign them a rank value from 10 to 0 based on their priority.

Step Three: Multiplying the rank values together yields the figure of merit values for the Part Three Entries.

The rationale for the power plant and priority rank are:

Safety: The ability of the gas turbine to provide 100% backing power under most situations gave it the highest rank. Steam and diesels considered about equal except slow-speed diesels do not require a prolonged warm-up period. Also the light-off period for the gas turbine is shorter than the steam plant; the steam plant may require one to two hours before it can deliver any power level.

Reliability: Steam ranks the highest owing to its proven reliability over the other two.

Maintainability: Gas turbine ranked highest due to the ability to exchange entire prime movers. Steam was next due to the ability to perform many maintenance items while the plant is operating.

Quietness: Steam turbine power plants are inherently the quietest of the three considered. Diesel plant is

worst due to the vibration it produces from its reciprocating action.

Factor Priority: Safety is considered paramount and therefore given the highest priority. The other factors follow in the listed order.

3.5 Life Cycle Cost [24, 25]

Ship power plant life cycle cost (LCC) may have many alternate forms depending on how the initial and operating costs of the various power plants are combined. One life cycle cost method converts all initial costs into equal parts for the estimated life of the ship and then adds one average annual part to the annual operating cost. This total is referred to as the Uniform Annual Cost (UAC) Method. For example:

$$\text{LCC(UAC Method)} = \left[\frac{\text{Initial Cost + Interest}}{\text{Estimated Life}}\right] + \left[\begin{array}{c}\text{Annual}\\ \text{Operating}\\ \text{Cost}\end{array}\right] \quad (5)$$

Another life cycle cost method converts annual power plant operating cost to Present Worth (PW) and adds PW to initial cost. Present worth is defined as:

$$\text{PW} = [\text{Annual Operating Cost}][\text{PW Factor}]$$

PW Factor is defined as:

$$\text{PW Factor} = \frac{(1 + i)^N - 1}{i\,(1 + i)^N} \quad (6)$$

where i is annual interest rate and N is the loan period in years. So LCC (PW Method) is

$$\text{LCC (PW Method)} = (\text{Initial Cost}) + (\text{PW}) \quad (7)$$

The present-worth method has been used in this study.

4. A WORKED EXAMPLE

The method outlined in the previous chapters has been used to examine a representative merchant ship having the following characteristics:

100,000 Gross Tons, 20,000 tons steel weight

16 knots, 26-foot diameter propeller

19,200 EHP (from model test or standard series calculation)

26 foot propeller (maximum)

4,000-mile range

280 days of operation per year

From these figures values of propulsion coefficient were determined using the Troost B series propeller characteristics, Appendix A. The predicted values of propulsion coefficient were 0.74 at 82 RPM and .70 at 100 RPM. The lower PC corresponds to the optimum design for a direct-drive diesel engine.

The design shaft horsepower of the prime mover is 26,000 at 82 RPM and 27,400 for the low-speed diesel at 100 RPM. At this point it is possible to evaluate the various power plant alternatives for selected values of interest rate and life cycle years. In this example the interest rate was assumed to be 7% and the life of the ship was taken as 25 years. Many of the calculations are the sample calculations in the Appendices.

The calculating results are summarized in Figures 4.1 and 4.2. The results indicate that for the example the steam plant and the diesel plant have similar life cycle costs which are considerably lower than the gas turbine plant. Figure of merit indicates the gas turbine plant to be slightly better than the steam plant while the diesel has the lowest rating.

POWER PLANT TYPE / NO. OF PROPELLERS		STEAM ONE	LOW SPEED DIESEL ONE	AIRCRAFT DERIVATIVE GAS TURBINE ONE	STEAM TWO } ETC.
PART NO.	PROBLEM FACTORS				
ONE	EHP/PC/SHP	19,200/0.74/26,000	19,200/0.68/27,400	19,200/0.74/26,000	
	TRIP MILES/SPEED	4000/16	4000/16	4000/16	
	OPERATIONAL DAYS PER YEAR	280	280	280	
TWO	LIFE CYCLE YEARS / ANNUAL INTEREST RATE	25/7%	25/7%	25/7%	
	INITIAL COST	$ 4.13 MILLION	$ 4.35 MILLION	$ 3.81 MILLION	
	PRESENT WORTH OPERATING COST	$ 13.55 MILLION	15.10 MILLION	21.40 MILLION	
THREE	SAFETY	50	60	90	
	RELIABILITY	72	64	64	
	MAINTAINABILITY	56	42	63	
	QUIETNESS	45	20	25	
FOUR	FIGURE OF MERIT	233	186	242	
	LIFE CYCLE COST	$ 17.68 MILLION	$ 19.45 MILLION	$ 25.21 MILLION	

Figure 4.1 POWER PLANT SUMMARY FOR 26,000 SHP REPRESENTATIVE SHIP

TYPE OF COST	POWER PLANT TYPE / NO. OF PROPELLERS	STEAM / ONE	LOW SPEED DIESEL / ONE	AIRCRAFT DERIVATIVE GAS TURBINE / ONE	} ETC.
INITIAL	POWER PLANT ACQUISITION AND INSTALLATION COST	$ 3.90 MILLION	$ 3.84 MILLION	$ 3.56 MILLION	
	HULL AND STRUCTURE COST DUE TO MANNING	0.25	0.31	0.21	
	HULL AND STRUCTURE COST DUE TO CHANGE IN FUEL RATE AND POWER PLANT WEIGHT	– 0.02	+0.08	–0.08	
	SUPPORT EQUIPMENT ACQUISITION COST	—	0.12	0.12	
	TOTAL ($)	4.13 MILLION	4.35 MILLION	3.81 MILLION	
OPERATING	MAINTENANCE AND REPAIR COST	0.047	0.124	0.091	
	MANNING COST	0.180	0.242	0.133	
	OUTAGE COST	0.117	0.187	0.240	
	FUEL COST	0.817	0.695	1.375	
	LUBE OIL COST	—	0.043	—	
	SUPPORT EQUIPMENT COST	—	—	—	
	TOTAL ($)	1.161 M	1.291 M	1.839 M	
	PRESENT WORTH FACTOR	11.68	11.68	11.68	
	PRESENT WORTH OPERATING COST ($)	13.55 M	15.10 M	21.40 M	

Figure 4.2 COST SUMMARY FOR 26,000 SHP REPRESENTATIVE SHIP

From these results the steam plant would be considered the best candidate and the aircraft derivate gas turbine plant would be eliminated from further consideration.

5. CONCLUSIONS

The main conclusions in this ship power plant selection study are as follows:

(1) A method has been developed for making a rational selection of type of power plant.

(2) Preliminary analysis of steam, slow-speed diesel and aircraft derivative gas turbine power plants has been carried out for the following representative conditions:

- 26,000 SHP for steam and gas turbine plants
- 27,400 SHP for diesel plant
- 16 knots
- 280 operating days per year

The results indicate:

(a) Steam and slow-speed diesel plants are about equal in cost for a twenty-five-year life.

(b) Aircraft derivative gas turbine plants are more costly than either the steam or diesel plants to operate.

(c) Gas turbine and steam propulsion plants have similar figure of merit while the diesel has a lower figure of merit for the qualitative factors considered.

(3) The power plant acquisition and installation cost and the annual fuel cost are the major inputs to the economic comparison.

(4) Even after simplifying the power plant selection problem for preliminary analysis it is still a complex problem with many factors to consider.

(5) It is possible in preliminary analysis to consider calculation of the propulsion coefficient and the effect of matching the propeller to the ship hull and to the prime mover.

(6) Ship power plant cost data is difficult to obtain owing to its proprietary nature. Limiting the search for such data to current literature leaves many gaps. The trends shown in the various data for calculating cost are representative and the costs developed from them, although not accurate per se, will allow comparison evaluation. The operating costs although simplified are estimated to be within 5% for the cost elements considered. The acquisition and installation cost is the least accurate and could vary by 10%.

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APPENDIX A. - REVIEW OF PROPELLER CHARACTERISTICS AND THE PROPELLER-SHIP MATCHING PROBLEMS

1. Steady State Propeller Characteristics [26, 27]

For a propeller, interest is not centered on the total force developed by the propeller, but the components in the axial direction and tangential directions. The component of force in the axial direction is thrust (T), and the component in the tangential direction times its moment arm is torque (Q); thrust and torque vectors are shown in Figure A.1. The steady state characteristics of the propeller are described by its torque, thrust, diameter and revolutions per unit time (n or RPM).

2. Pitch, Slip and Slip Ratio [2, 5]

With a screw propeller, as with a wood screw or metal bolt, the axial distance advanced with each complete revolution is known as the pitch (P). The path of advance of each propeller blade is only approximately helicodal owing to water not being a solid medium, which means there will be a difference in actual and theoretical advance distance or advance velocity; this difference is called Slip. Using velocity vectors, slip velocity is illustrated in Figure A.2.

When the slip velocity (V_{SLIP}) is expressed as a function of the ship velocity (V) through the water, the ratio of V_{SLIP} to V is defined as slip ratio (s).

$$s = \frac{V_{SLIP}}{V} \qquad (8)$$

From Figure A.2

$$V_{SLIP} = V_A - nP \qquad (9)$$

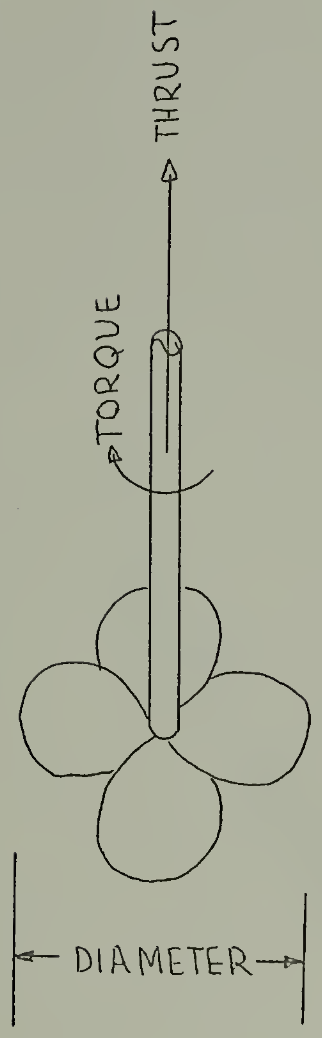
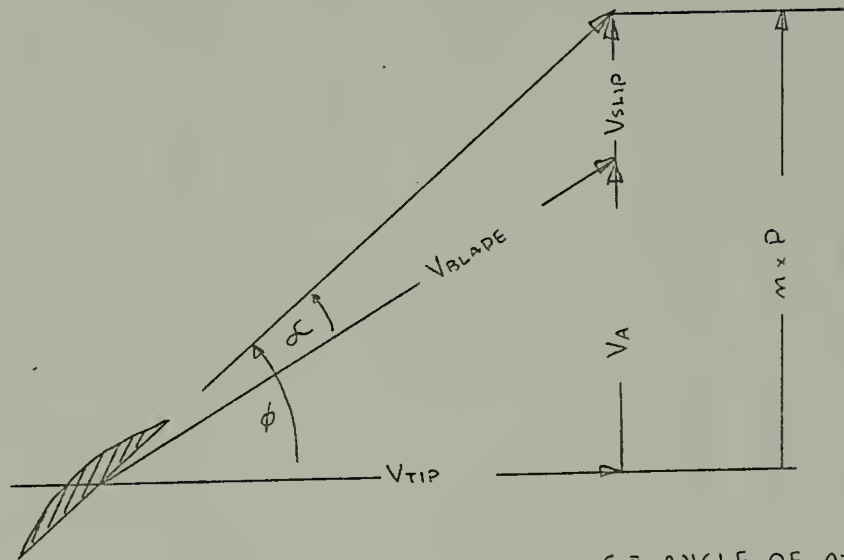


Figure A.1 PROPELLER STEADY STATE CHARACTERISTICS [26]



$\alpha \equiv$ ANGLE OF ATTACK

$\phi \equiv$ PITCH ANGLE

$\tan \phi = P/\pi D$

Figure 4.2 DEFINITION OF SLIP [2]

so

$$s = \frac{V_A - nP}{V} \tag{10}$$

Another slip ratio, defined as true slip ratio (s^*), is a ratio of V_{SLIP} to P X n

$$s^* = \frac{V_{SLIP}}{Pn} = \frac{V_A}{Pn} - 1 \tag{11}$$

3. Torque and Efficiency as a Function of Slip Ratio [2, 5, 6]

Using the momentum theory for propeller action and the slip ratio, it can be shown that thrust (T) and ideal propeller efficiency (ηPI) are

$$T = \frac{\rho \pi D^2 \; V_A^2}{4} \; (1 + s/2) \; (s) \tag{12}$$

and

$$\eta_{PI} = \frac{1}{1 + (s/2)} \tag{13}$$

V_A is the velocity of the water at the propeller, V_A is greater than V; D is propeller diameter and ρ is water density.

Study of these expressions for T and η_{PI} shows that s should be large for high thrust, but small for high efficiency. Accordingly, a compromise on s is necessary, and from the T equation choosing the largest diameter possible for the propeller allows this compromise to be the best possible.

4. K_T, K_Q, η_{PO} and J Propeller Characteristics [2, 5]

A convenient method of presenting propeller characteristics uses: torque coefficient (K_Q), a measure of input; a thrust coefficient (K_T),

a measure of output; the propeller efficiency (η_{PO}) and the advance coefficient (J), a measure of slip. The advance coefficient and true slip ratio may be correlated as follows:

· $J = \dfrac{V_A}{nD}$

From Figure A.2, $D = P/(\pi \tan\phi)$

Then, $J = (\pi \tan\phi) \quad V_A/nP$ (14)

· $s^* = \dfrac{V_{SLIP}}{nP}$

From (Eqn. 9), $V_{SLIP} = nP - V_A$

so, $s^* = 1 - \dfrac{V_A}{nP}$ (15)

· Comparing equations 14 and 15, it is seen that J and s^* are both functions of V_A, n and P. It is concluded, therefore, that J is also a measure of slip.

When the propeller is operating fully submerged, not in close proximity of a ship hull and non-cavitating, then the characteristics for the propeller are called open-water characteristics. A typical plot of these open-water characteristics is shown in Figure A.3.

The defining equations for K_T, K_Q, η_{PO} and J are useful in understanding the propulsion coefficient to be derived below, and for techniques used in propeller selection based on hull-propeller matching. These equations are:

$J = V_A/nD$ (16)

$K_T = T/\pi D^4 n^2$ (17)

$K_Q = Q/\pi D^5 n^2$ (18)

$\eta_{PO} = (K_T/K_Q)\ (J/2\pi)$ (19)

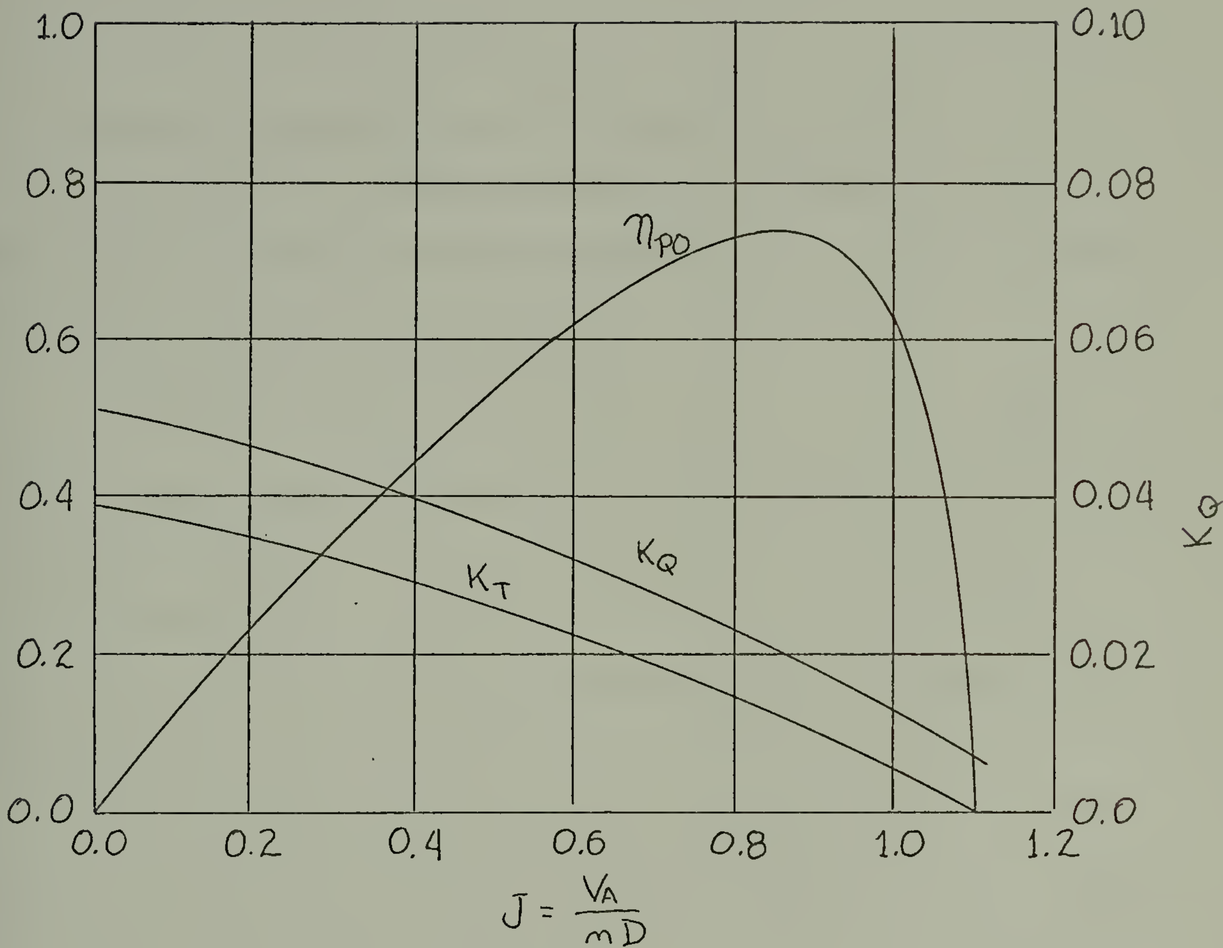


Figure A.3 TYPICAL OPEN-WATER FIXED PITCH PROPELLER CHARACTERISTICS [5]

where:

V_A - is velocity of the water the propeller works in

D - diameter of the propeller

ρ - density of water

n - revolutions per second

5. Interaction Between Ship Hull and Propeller [2, 26]

By experiment, it is found that there is a difference between the velocity of the water the propeller operates in (V_A) and the ship velocity (V). A wake fraction (w) is defined as:

$$w = \frac{V - V_A}{V} = 1 - \frac{V_A}{V} \tag{20}$$

or more normally seen in the form (1-w) which is the proportionality factor between V_A and V.

$$V_A = (1-w)\ V \tag{21}$$

Wake fraction (w) is one of the two correlating factors between ship hull and propeller.

Owing to the acceleration of water at the stern of the ship by the propeller the thrust (T) necessary to propel the ship is greater than the bare hull resistance (R). A thrust deduction factor (t) is defined as

$$t = \frac{T - R}{T} \tag{22}$$

or more normally seen in the form (1-t) which is the proportionality factor between R and T so that

$$R = (1-t)\ T \tag{23}$$

And thrust deduction factor is the other correlating factor between the hull and propeller.

6. Propulsion Coefficient - PC [2, 26,27]

As defined in Chapter 2 the propulsion coefficient is

$$PC = \frac{EHP}{SHP} \tag{24}$$

Shaft horsepower may be determined from the propeller torque of the self-propelled ship (Q_{sp}), propeller revolutions per second (n), consideration of shaft torque transmission efficiency so

$$SHP = Q_{sp}\ 2\pi n/(\eta_{SHAFT} \times 550) \tag{25}$$

From equation 2 effective horsepower is

$$EHP = \frac{R \cdot V}{550}$$

Equation 24 then may be written as

$$PC = \frac{R \cdot V \quad \eta_{SHAFT}}{Q_{sp} \cdot 2\pi n} \tag{26}$$

Using equations 16, 17, 18, 21, 23 and multiplying the right-hand side by V_A/V_A and K_Q/K_Q, it may be shown that

$$PC = \left(\frac{1 - t}{1 - w}\right)\left(\frac{J\ K_T}{2\pi K_Q}\right)\left(\frac{K_Q}{(K_Q)_{sp}}\right) \tag{27}$$

where the elements of equation 27 are as follows:

$$\left(\frac{1 - t}{1 - w}\right) = \text{hull efficiency } (\eta_{hull}) \tag{28}$$

$$\left(\frac{J}{2\pi}\frac{K_T}{K_Q}\right) = \text{open water propeller efficiency } (\eta_{PO}) \tag{29}$$

$$\left(\frac{K_Q}{(K_Q)_{sp}}\right) = \text{relative rotative efficiency } (\eta_r) \tag{30}$$

$$\eta_{SHAFT} = \text{propeller shaft transmission efficiency} \tag{31}$$

then

$$PC = \eta_{hull}\ \eta_{PO}\ \eta_r\ \eta_{SHAFT} \qquad (32)$$

The propulsion coefficient is a function of four other efficiencies. Since t, w, K_Q/K_{Qsp} may be assumed to be constant and losses due to η_{SHAFT} are negligible, then PC may be seen to be a function only of open-water propeller efficiency. Preliminary prediction of PC is then possible.

7. Open-Water Propeller Efficiency [5, 26]

Review of Figure A.3 will illustrate the sensitivity to open-water propeller efficiency as a function of the advance coefficient. Assuming the search is for maximum propeller efficiency and if t and w are constant, which implies V_A is known, then η_{PO} will be a function of n and D only. η_{PO} as a function of n and D is shown in Figure A.4; the greater the propeller diameter the greater η_{PO}. This supports the conclusion in paragraph A.3 that propeller efficiency increases with diameter. Also it is shown in Figure A.4 that η_{PO} may occur at a lower RPM (or n) for incremental increases in the propeller diameter.

8. Matching Propeller and Ship Hull Characteristics [2,3,5, 6, 27, 28, etc.]

The objective of propeller-ship matching is to get the propeller to operate near its maximum efficiency with as large a propeller diameter as the ship's geometry and external ship characteristic will allow. Effective horsepower is the power to propel the design ship hull. Propeller horsepower is the power required to rotate the propeller(s). Power is therefore common to both the ship hull and the propeller.

Using the basic expression for horsepower

$$EHP = R \cdot V/550$$

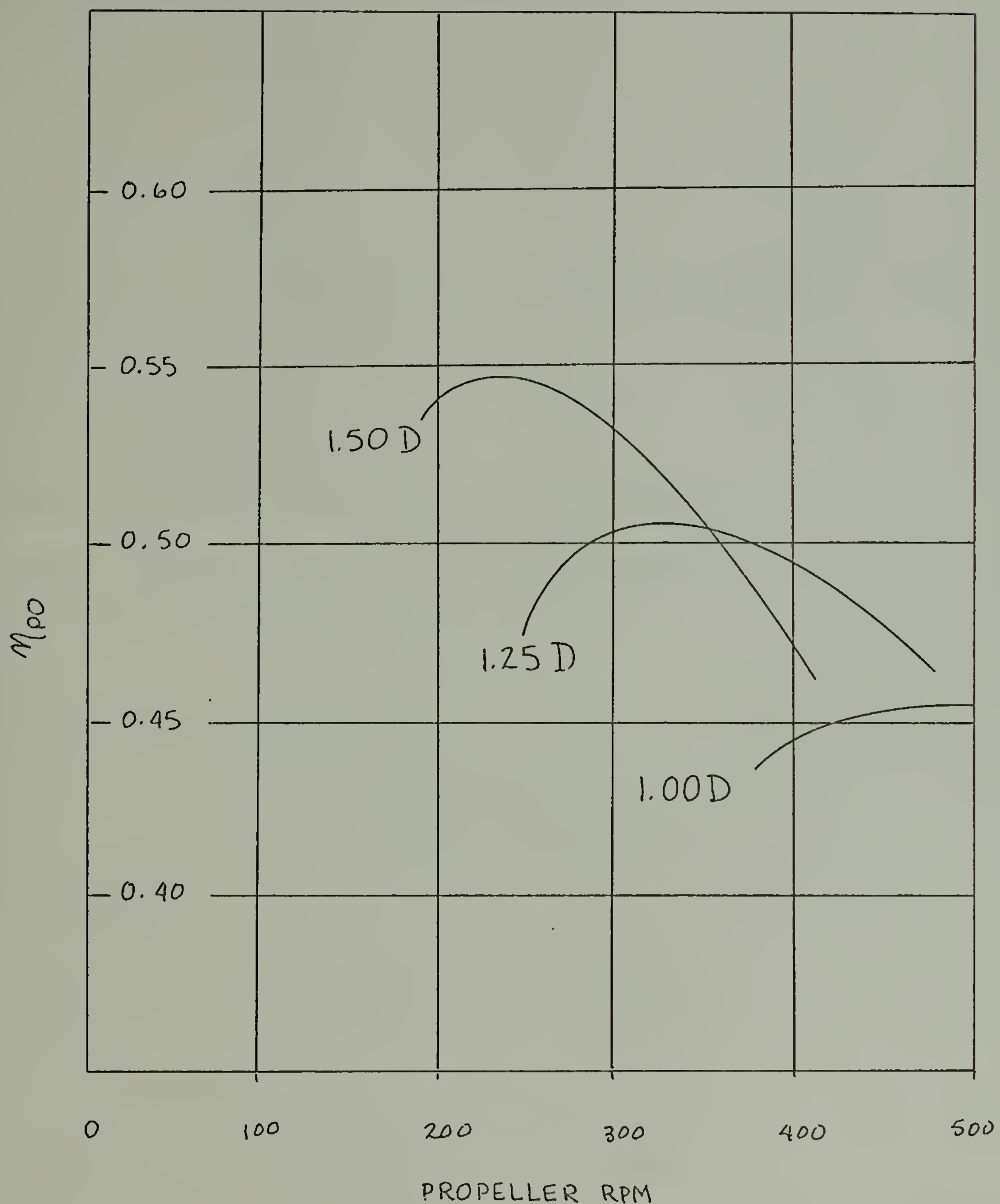


Figure A.4 PROPELLER EFFICIENCY AS A FUNCTION OF DESIGN RPM AND DIAMETER [6]

(with V in feet per second and R in pounds force)

substituting

$R = (1 - t)T$ and $V = V_A/(1 - w)$

then

$$EHP = T \frac{(1 - t)}{(1 - w)} \frac{V_A}{550} \tag{33}$$

Dividing both sides of Equation 33 by V^3 and solving for $K_T D^2/J^2$ using equations 16 and 17 it can be shown that

$$\frac{K_T D^2}{J^2} = \frac{EHP}{V^3} \frac{550}{\rho(1 - w)^2 (1 - x)} \tag{34}$$

The important correlation between propeller characteristics and external ship characteristics is then established. For purposes of this analysis ρ will be considered a constant then

$$\frac{K_T D^2}{J^2} = (\text{constant})(ESC(EHP, V)) \tag{35}$$

where ESC stands for external ship characteristics.

K_T/J^2 is also a function of thrust and velocity.

$$\frac{K_T}{J^2} = \frac{T/\rho n^2 D^4}{V_A^2/n^2 D^2} = \frac{T}{\rho D^2 V_A} \tag{36}$$

again considering ρ a constant now

$$\frac{K_T}{J^2} D^2 = (\text{constant})\ (ESC(T,V)) \tag{37}$$

which supports the derivation for ESC (EHP, V) above.

If ESC/D^2 is constant it could be easily plotted as a function of K_T and J. From Equations 35 and 37, assuming t, w and D are constants and that ESC (EHP, V) equals ESC (T, V), it follows

$$\frac{T}{V^2} \propto \frac{EHP}{V^3} \propto ESC$$

But

$$T \propto R(R, F)$$

The external ship characteristic is a function of Froude Number (F) and Reynolds Number (R) which are both related to ship geometry and ship speed.

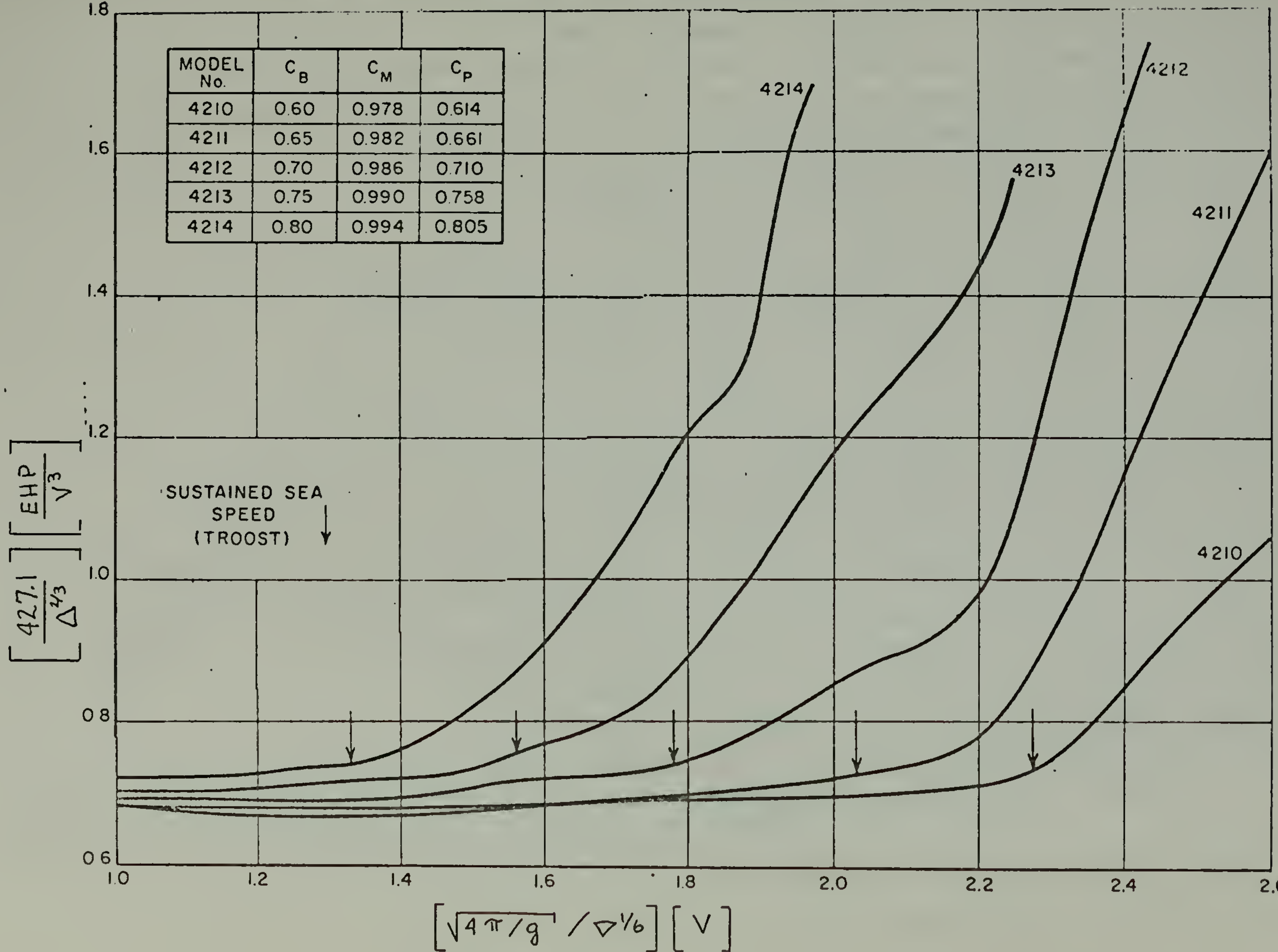
It is seen in Figure A.5 that (EHP/V^3) is plotted as a function of (V) for various ship hull geometries. The (EHP/V^3) curves have sections that change very slightly with (V). The sustained sea speed of most commercial ships is about where the arrows are in the figure. These arrows are on the sections of the curves that are almost constant. It is concluded therefore, that for ships of economic interest ESC may be assumed constant.

With ESC assumed to be constant a numerical value for it may be calculated. Then

$$\frac{K_T}{J^2} = \text{constant} \qquad (38)$$

Figure A.6 taken from reference [28] is a K_T, K_Q, η_{PO}, J propeller chart for a four-bladed propeller showing several propeller pitch-to-diameter ratios. Reference [28] uses different nomenclature for propeller characteristics; information in Figure A.7 is used for nomenclature conversion.

A typical ESC calculation is shown in paragraph A.9. The result is used to plot the K_T/J^2 line in Figure A.8. Since the propeller and the ship only operate together at one point for a given ship speed, the various pitch-to-diameter ratios allow several choices. To minimize shaft



MODEL No.	C_B	C_M	C_P
4210	0.60	0.978	0.614
4211	0.65	0.982	0.661
4212	0.70	0.986	0.710
4213	0.75	0.990	0.758
4214	0.80	0.994	0.805

Figure A.5 EHP/V^3 AS A FUNCTION OF V FOR VARIOUS SHIP GEOMETRIES [15]

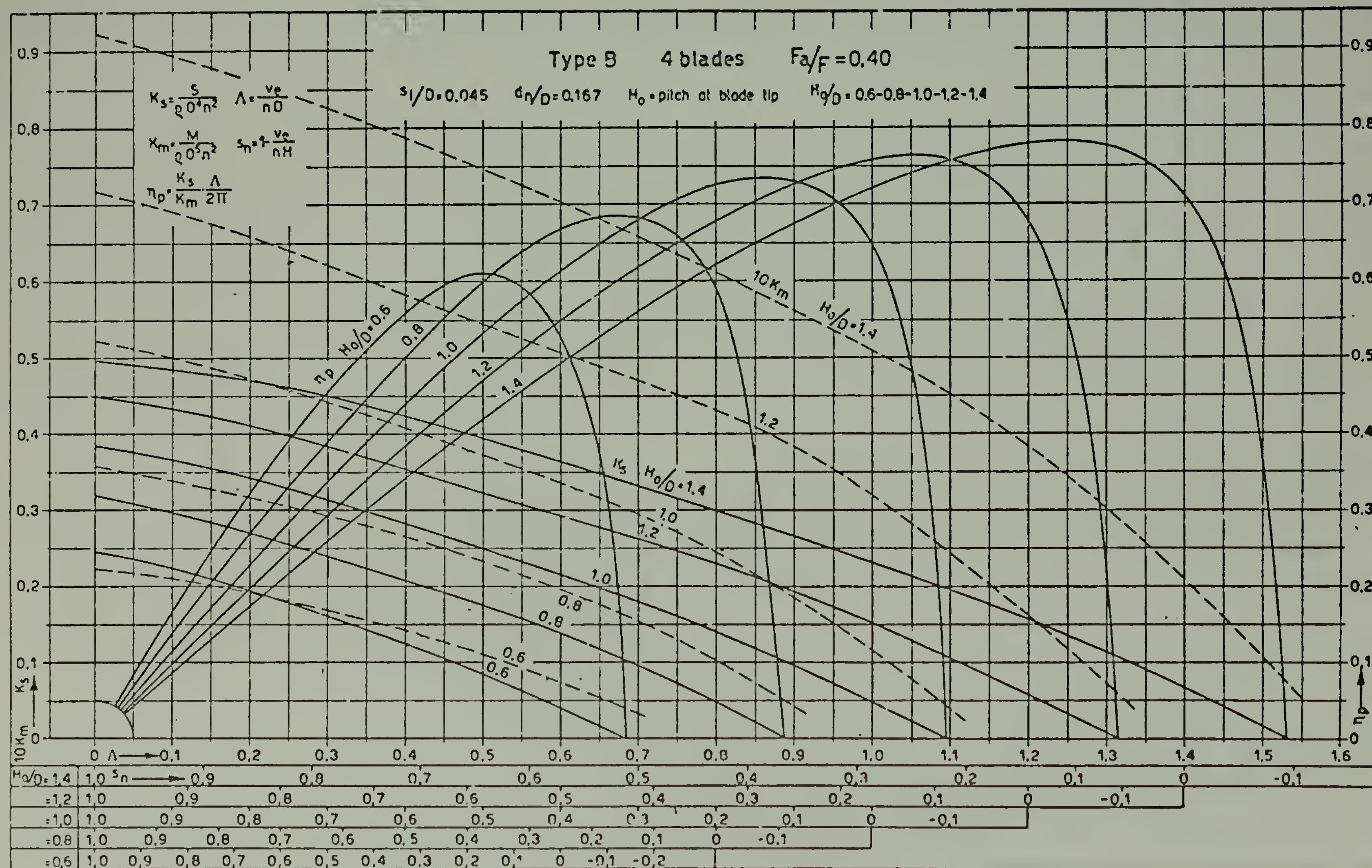


Figure A.6 K_T, K_Q, η_{PO}, J PROPELLER CHART [28]

TROOST PROPELLER SERIES

The attached curves show the performance of Troost's B-series propellers using standard K_T-K_Q-J coefficients. The following is a table of equivalent symbols:

TROOST CURVES	
K_s	K_T
K_m	K_Q
Λ	J
η_P	η_{PO}
S_n	true slip (s*)
H/D, H_o/D	P/D
S_i/D	Blade thickness fraction
d_n/D	Hub dia./prop. dia.
F_a/F	Exp. area ratio

FIGURE 3.7 NOMENCLATURE FOR FIGURE 3.7 [26]

horsepower the objective is to maximize η_{P0}. η_{P0} max may be determined from a η_{P0} locus line also shown in Figure A.8.

η_{P0} max then has a corresponding advance coefficient from which the optimum propeller RPM may be determined. A sample propeller RPM calculation is outlined in the following paragraph.

9. Calculation of Propeller RPM and Propulsion Coefficient for 26,000 SHP Ship

Given:

- One fixed-pitch propeller, four blades
- V Max (KTS) = 16.0
- EHP at V Max (HP) = 19,200
- Propeller diameter (ft) = 26
- t = 0.2, see reference [2]
- w = 0.42, see reference [2]
- ρ = (salt water mass density at 59° F.) (lb-sec^2/ft^4) = 1.99

To Determine: Optimum propeller RPM and corresponding PC

(1) $$K_T/J^2 = \frac{EHP}{V^3} \quad \frac{550}{\rho(1-w)^2\,(1-t)\,D^2}$$

$$= \frac{19{,}200}{(16 \times 1.69)^3} \times \frac{550}{1.99} \times \frac{1}{(26)^2} \times \frac{1}{(1\text{-}.42)^2} \times \frac{1}{(1-.2)}$$

$$\therefore \underline{K_T = 1.06J^2}$$

(2) Construct η_{P0} locus line; see Figure A.8.

(3) From Figure 3.9 at η_{P0} max J = 0.42.

(4) $$n = \frac{V_A}{JD} = \frac{V(1-w)}{JD},$$

$$\cdot\ n = \frac{(16 \times 1.69)}{(0.43)} \ \frac{(1 - 0.42)}{(26.0)} = 1.37 \ \frac{\text{rounds}}{\text{sec}}$$

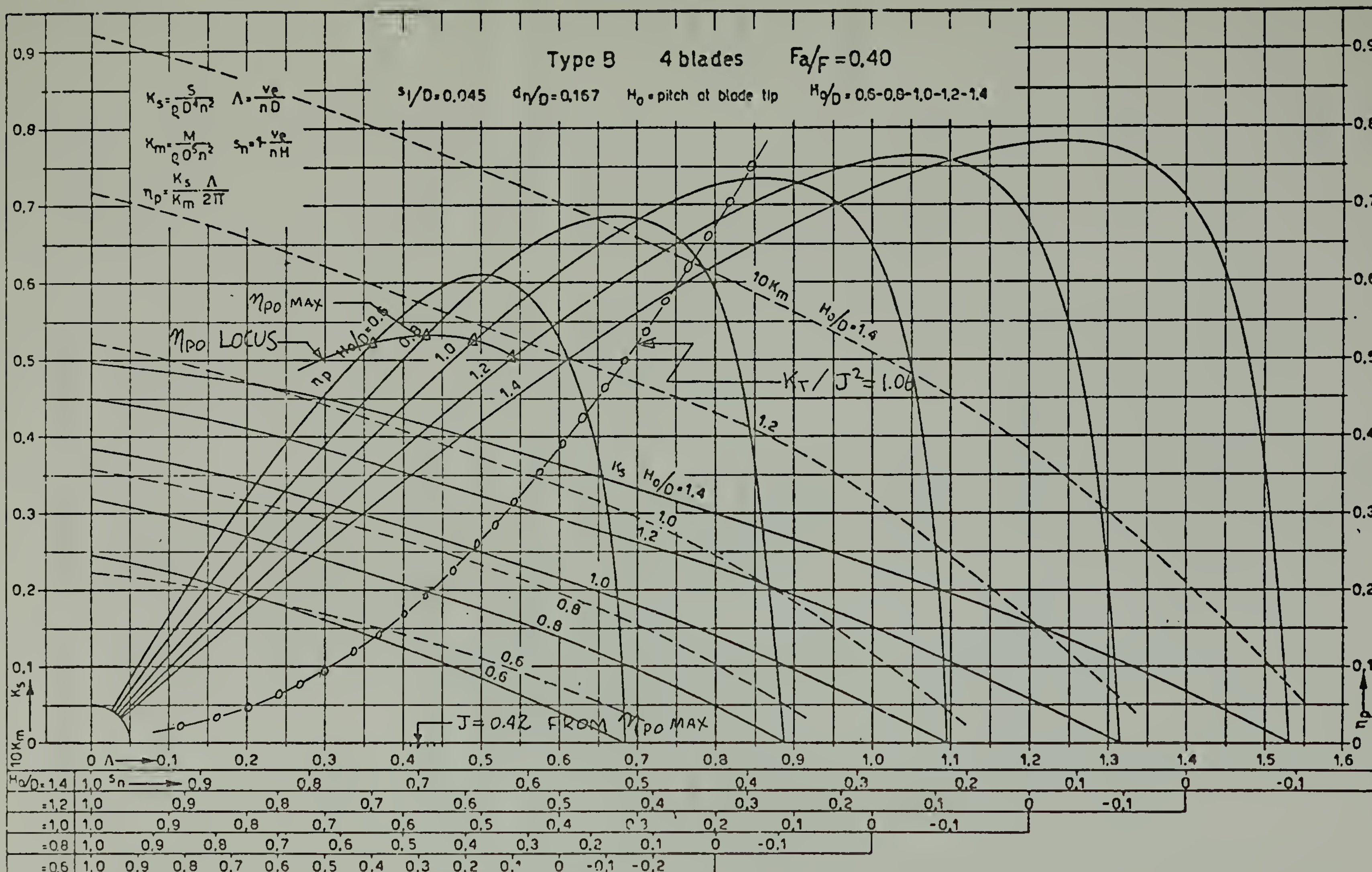


Figure A.8 K_T/J^2 AND η_{PO} LOCUS PLOTTED ON PROPELLER CHART [28]

* RPM = 82

(5) PC = $\eta_r \, \eta_{PO} \, \eta_{hull} \, \eta_{shaft}$,

* Assume η_{shaft} = .98, see reference [4]
* Assume η_r = 1.05, see references [2, 26]
* From Figure 3.9 η_{PO} max = 0.54

$$PC = (1.05)(0.54)\frac{(1 - 0.2)}{(1 - 0.42)}(.98) = 0.74$$

* PC = 0.74
* SHP = 26,000

10. Cavitation [2, 26, 27]

If the propeller is modeled as a disc with area $\pi D^2/4$, then the thrust is produced by a pressure difference across the disc. For forward thrust, the pressure on the forward side of the disc must be less than the pressure on the after side. For a given propeller diameter the greater the thrust the greater the pressure decrease on the forward side of the disc. Cavitation, the boiling of water owing to decrease in pressure below the vapour pressure, may be produced. Cavitation will reduce thrust and cause possible erosion to the propeller blades. The amount of thrust obtained from a given propeller is therefore limited.

The limitation on how much power can be applied to the propeller is often not within the capability of the acceptable engines, but has to do with the capability of the propeller to use the power without cavitation.

The propeller selection analysis should also include consideration for the effects of cavitation. Cavitation erosion will cause loss of propulsion efficiency and imbalance the propeller. The propeller imbalance may cause

additional loss in efficiency as well as mechanical damage to shafting, thrust bearing, prime mover and ship structure.

APPENDIX B. - POWER PLANT ACQUISITION AND INSTALLATION COSTS [22, 29, etc.]

Power plant acquisition and installation cost is calculated using data presented in Figure B.1. This data has been normalized to 1970 U. S. dollars using wage prices and man-hour information from reference [29]. The data also includes 66% overhead charge for installation costs.

Sample acquisition and installation cost calculation for 26,000 SHP steam plant:

- Given: 26,000 SHP steam plant
- Enter Figure B.1 with 26 (SHP/1000)
- From Figure B.1 ($/SHP) is 160
- $$160 \frac{\$}{\text{SHP}} \times 26{,}000 \text{ SHP} = 4.16 \times 10^6 \text{ dollars}$$
- Acquisition and Installation Cost ($) = 4.16 million

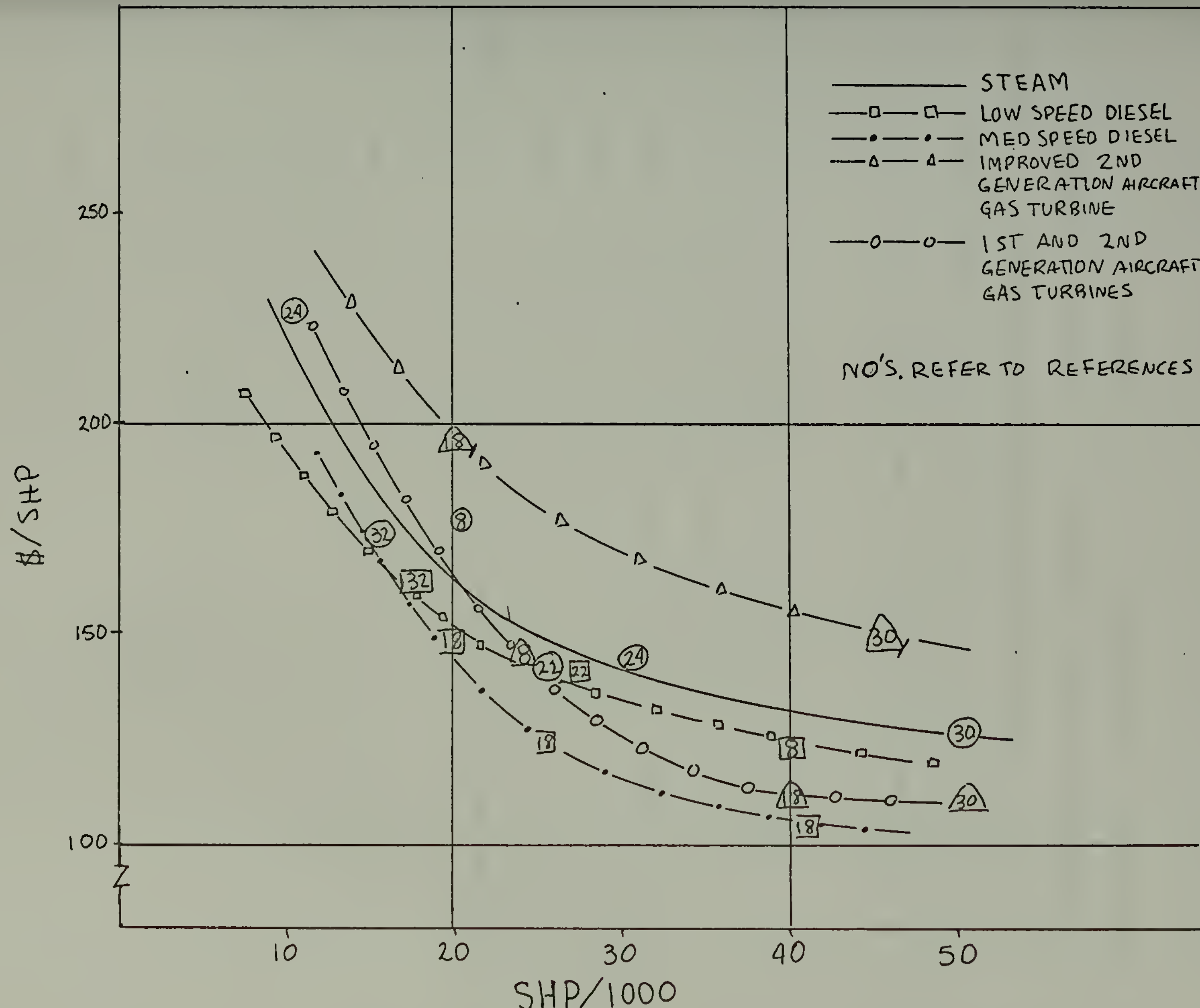


Figure B.1 ACQUISITION AND INSTALLATION COSTS FOR VARIOUS POWER PLANT TYPES

Data normalized to 1970 U.S. Dollars

APPENDIX C. - HULL AND STRUCTURE COSTS DUE TO MANNING [8, 22, 24, 29]

The hull and structure costs due to manning are calculated using data and information listed below. These costs include the steel and furnishings necessary to accommodate the engineering crew for the ship.

Data for making the hull and structure costs calculation is estimated using information from references [12] and [23] and normalizing it to 1970 U.S. dollars.

Hull and Structure Costs 1970 U. S. Dollars [8, 22, 24, 29]

- Man-hour cost per unit accommodation is 2000 man-hours.
- Cost of steel and furnishings is $7,000 per accommodation.
- Labor cost is $4.07/man-hour.
- Overhead cost using information from reference [22] is 66%.

Example hull and structure cost due to manning for fifteen accommodations:

- Given: 15 accommodations
- Labor cost is $4.07 per man-hour.
- Overhead cost is 66%.
- Cost ($/man-hour) is 6.78

$$2000 \text{ man-hours} \quad \frac{\$6.78}{\text{man-hour}} \quad 15 = \$203{,}000$$

$$\$7{,}000 \times 15 \qquad\qquad = \underline{\$105{,}000}$$

$$\$308{,}000$$

- Cost ($) = 0.308 million

APPENDIX D. - HULL AND STRUCTURE COST DUE TO % CHANGE IN FUEL RATE AND POWER PLANT WEIGHT [24, 29, 33]

The hull and structure cost due to % change in fuel rate and power plant weight is calculated using data and information from references [24], [29] and [33], which is presented in the figures of this appendix. Reference [33] provides the data to convert power plant weight and fuel rate into a hull weight change. Reference [24] provides data to convert hull weight change into cost by considering man-hours required to erect the additional steel and the steel cost. And reference [29] is used to develop 1970 U.S. dollar wage costs.

The weight data for various propulsion plants is shown in Figure D.1. This data is developed from current literature. Sample hull and structure cost calculation due to % change in fuel rate and power plant weight for a 26,000 SHP, 16 KT, 4000-mile range cargo ship with about a 20,000 net tons steel hull.

- A summary table with entries using data from Figures D.3, D.4, D.5, D.6, and D.7 is shown in Figure D.2. The entries were made assuming the 16-knot and the 20-knot ship were the same for the 4000-miles trip vice interpolating the graphs.
- Cost of steel is estimated to be \$360.00 per net ton.
- Man-hour cost from Figure D.8 is $\frac{\text{57 man-hours}}{\text{ton}}$.
- Labor cost + 66% overhead is $\frac{\$6.78}{\text{man-hour}}$.
- Cost Summary

Cost Summary (From Figure D.2)

Plant Type	ΔW (ton)	Steel Cost ($)	Man-hour Cost ($)	Total ($)
Steam	(-) 30	-10,800	-11,600	-22,400
Slow-speed diesel	(+) 100	+36,000	+38,600	+74,600
Gas Turbine	(-) 73	-26,300	-48,200	-74,500

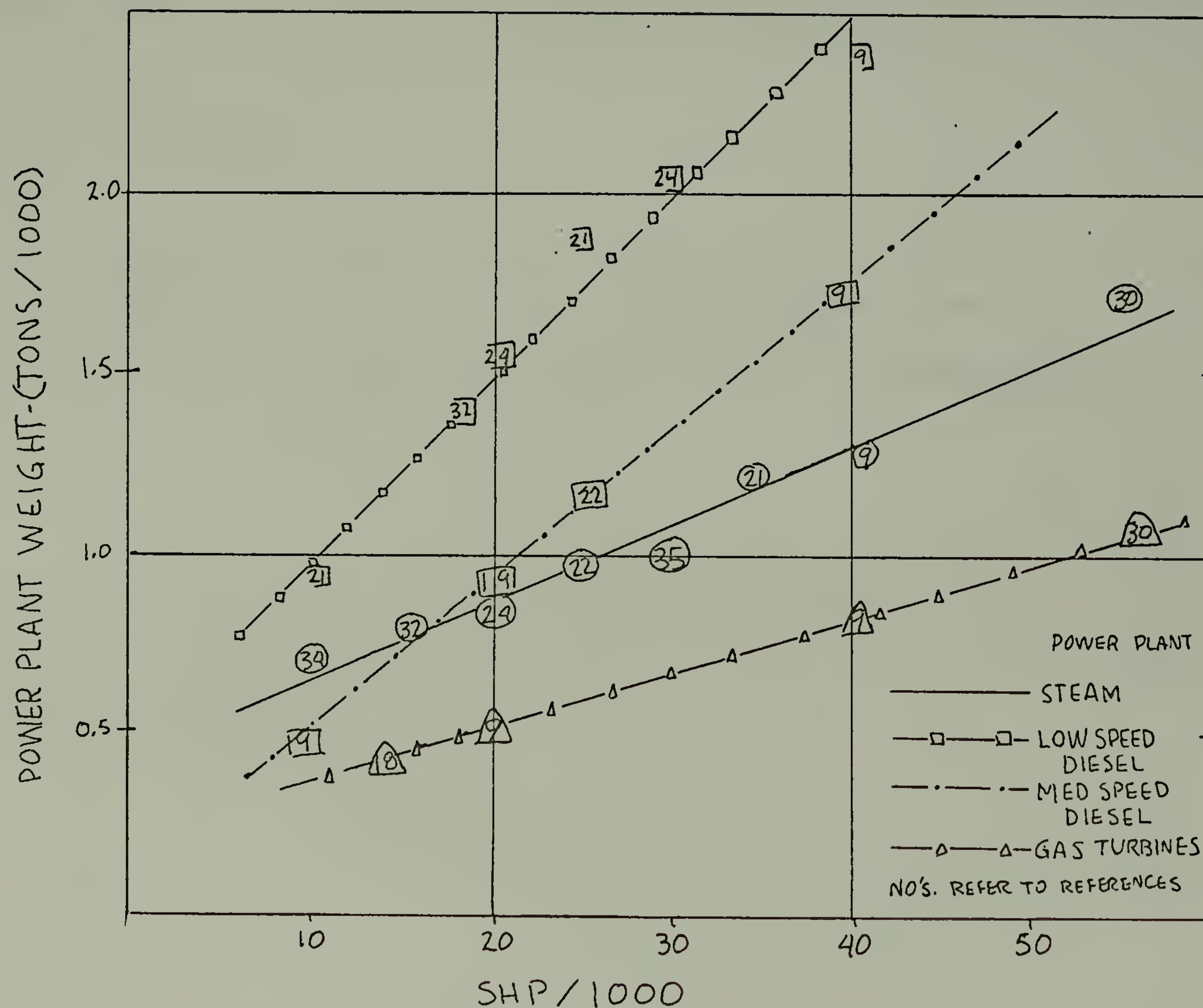


Figure D.1 POWER PLANT WEIGHT FOR VARIOUS TYPES OF POWER PLANTS

26,000 SHP SHIP
SPEED - 16 KTS
4000 MILE RANGE
20,000 NET TONS STEEL

	POWER PLANT WEIGHT (TONS)	%ΔW	ΔSHP FROM FIG. D.4	ΔW (TONS) FROM FIG. D.5	FUEL RATE [lbs fuel / SHP-hr]	%ΔFUEL RATE	ΔSHP FROM FIG. D.6	ΔW (TONS) FROM FIG. D.7	TOTAL ΔW (TONS)
BASE SHIP SEE FIG. D.3	1075				0.468				
STEAM, SEE FIG'S D.1 & 1.1	1000	-0.07	30	-30	0.450	-0.04	5	—	-30
LOW SPEED DIESEL SEE FIG'S. D.1 & 1.1	1750	+0.63	280	+125	0.356	-0.24	-40	-25	+100
GAS TURBINE SEE FIG'S. D.1 & 1.1	620	-0.42	180	-85	0.525	+0.12	+20	+12	-73

Figure D.2 SUMMARY FOR CHANGE IN SHIP STEEL WEIGHT DUE TO CHANGE IN FUEL RATE AND MACHINERY WEIGHT

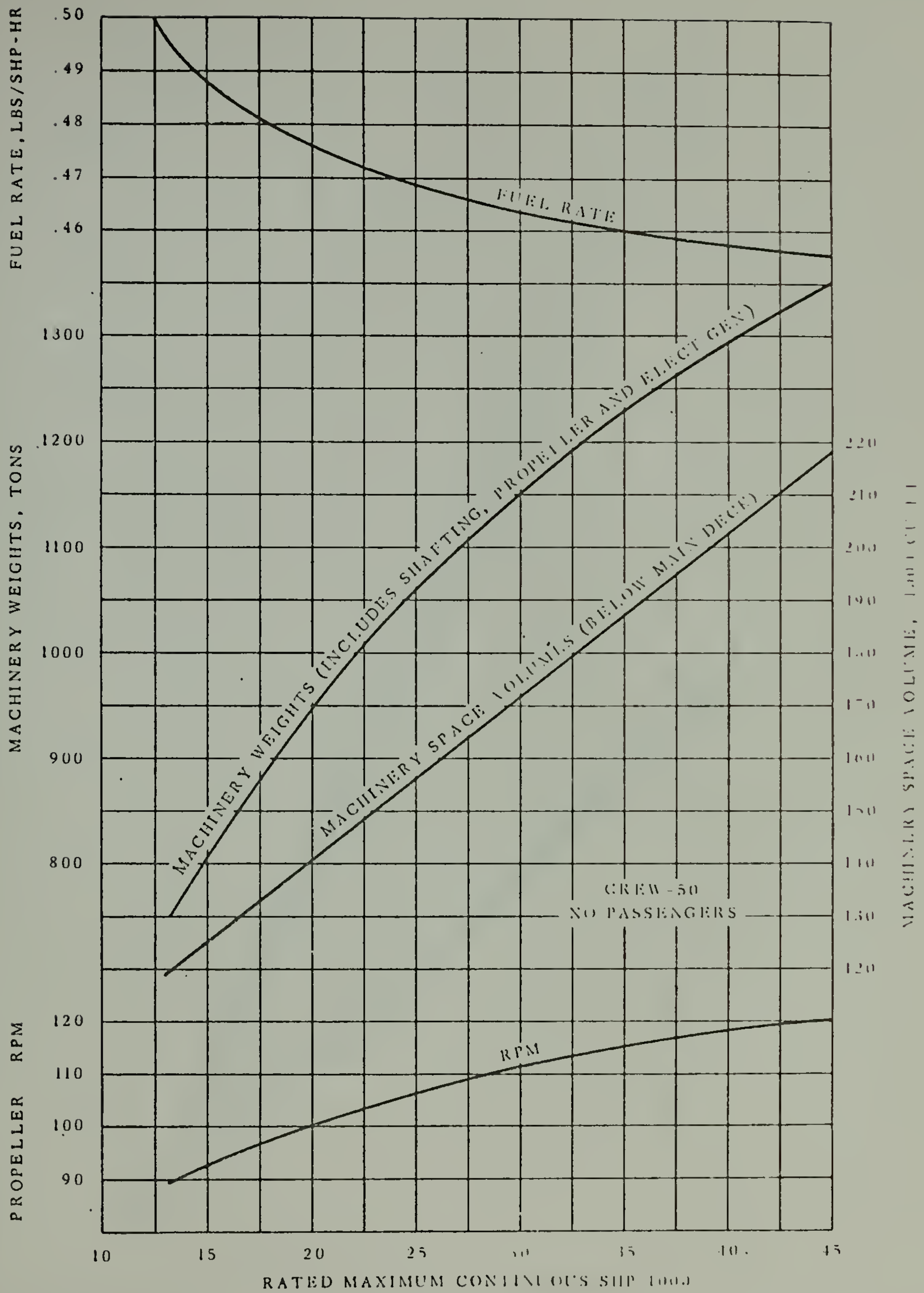


Figure D.3 BASIC NORMS USED FOR FUEL RATE AND MACHINERY WEIGHT [33]

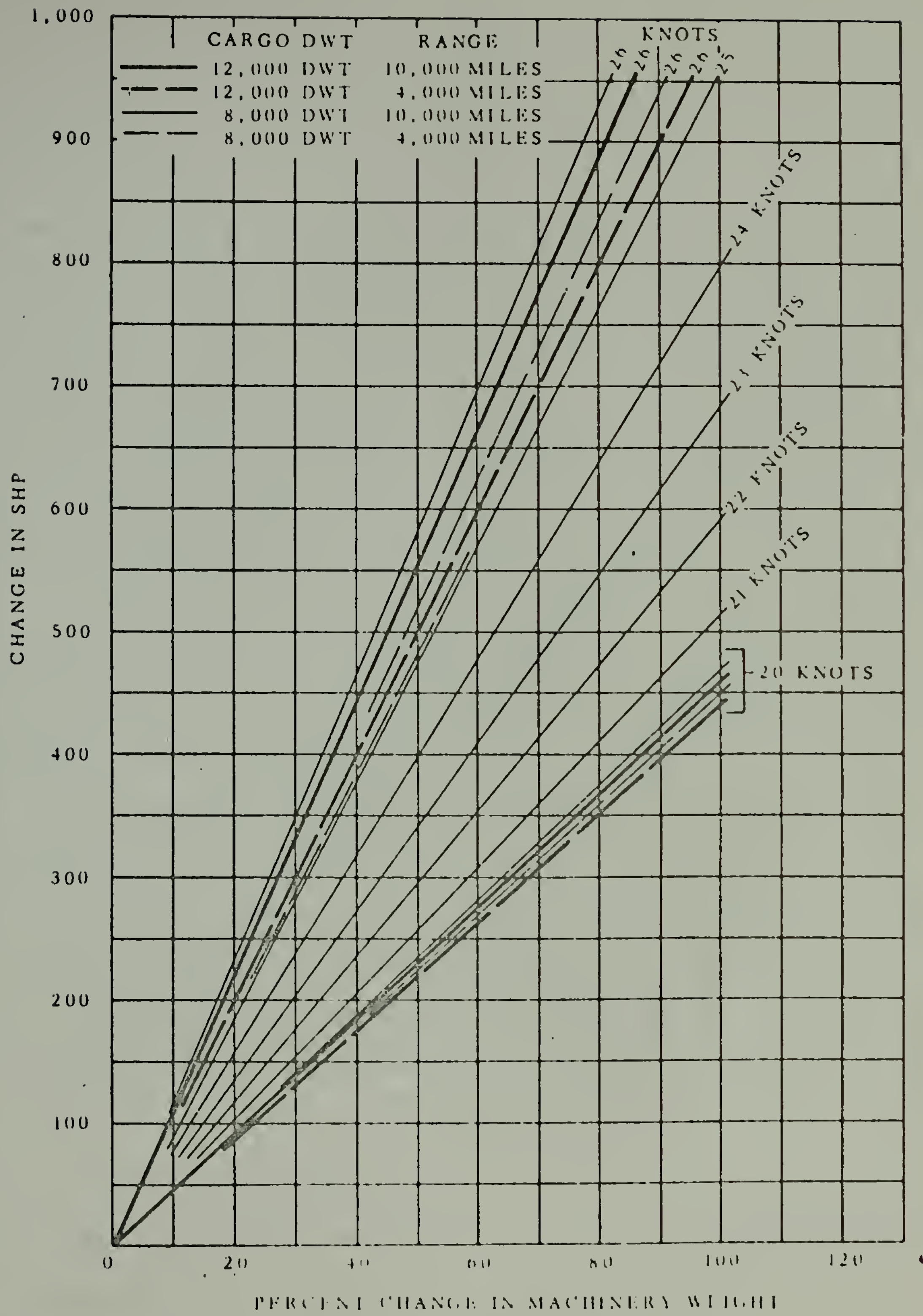
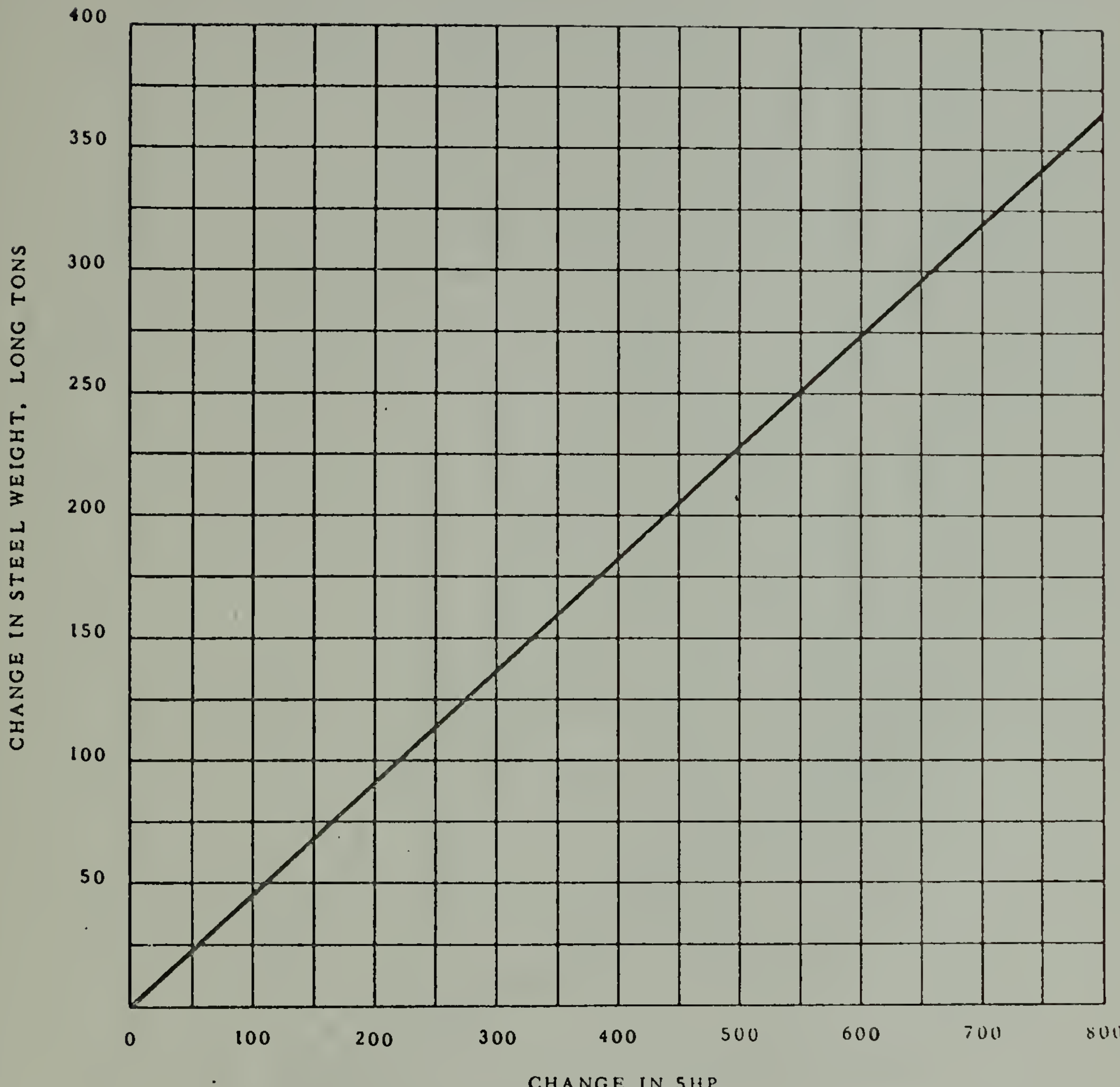


Figure D.4 EFFECT OF CHANGE IN MACHINERY WEIGHT ON SHP [33]



igure D.5 EFFECT OF CHANGE IN SHP ON WEIGHT OF STEEL DUE TO MACHINERY-WEIGHT CHANGE [33]

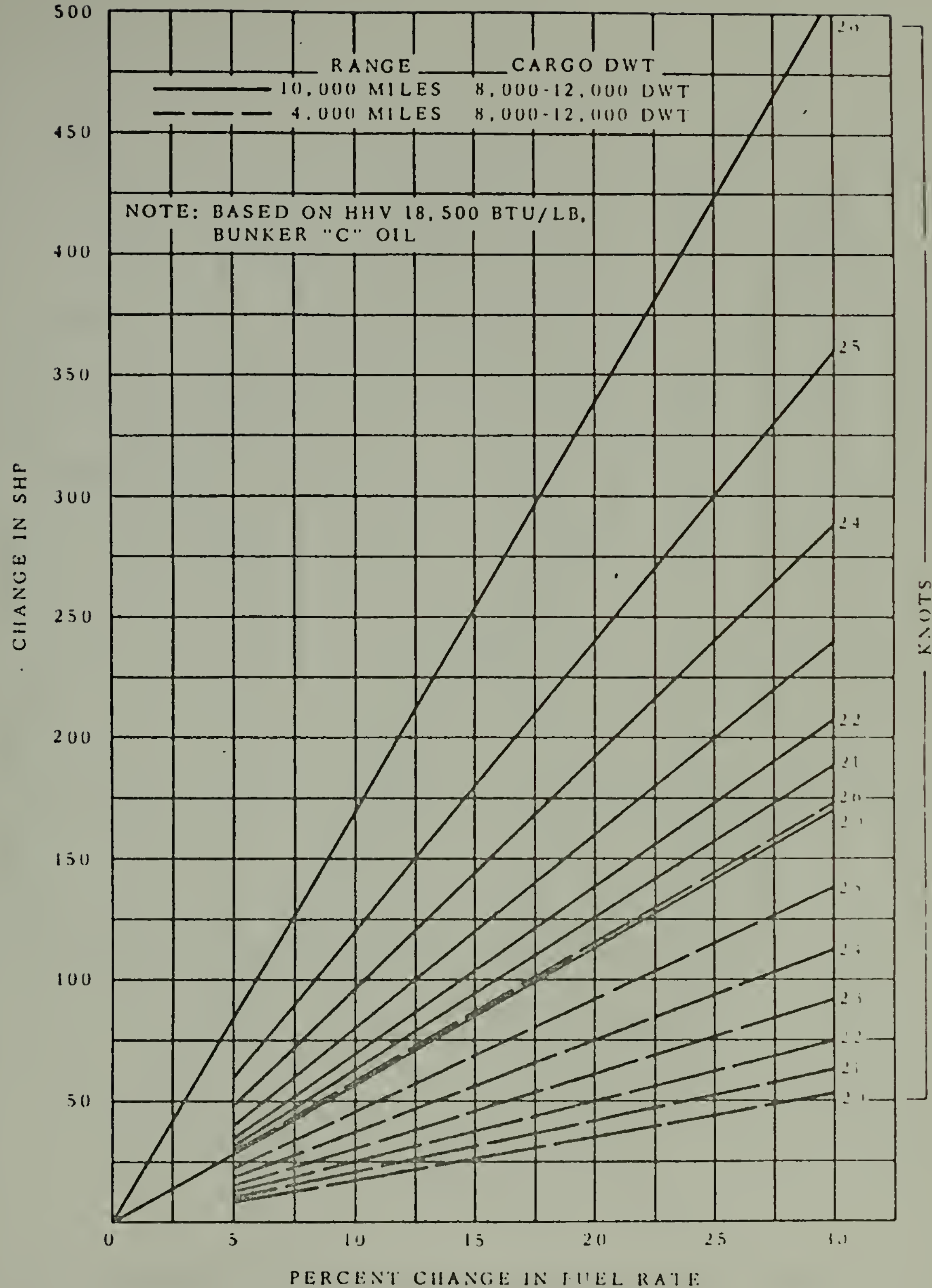


Figure D.6 EFFECT OF CHANGE IN FUEL RATE ON SHP [33]

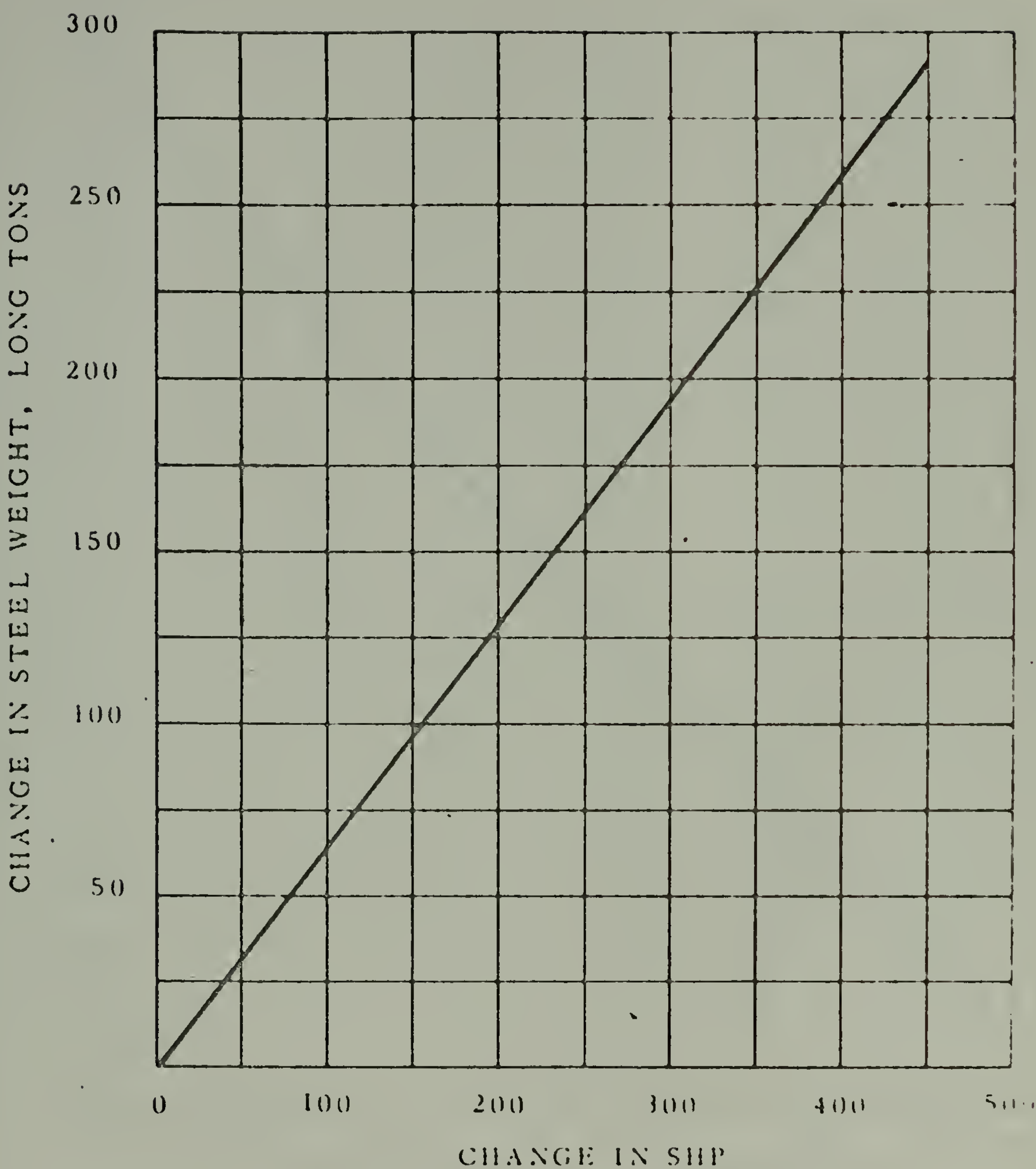


Figure D.7 EFFECT OF CHANGE IN SHP ON WEIGHT OF STEEL DUE TO FUEL-RATE CHANGE [33]

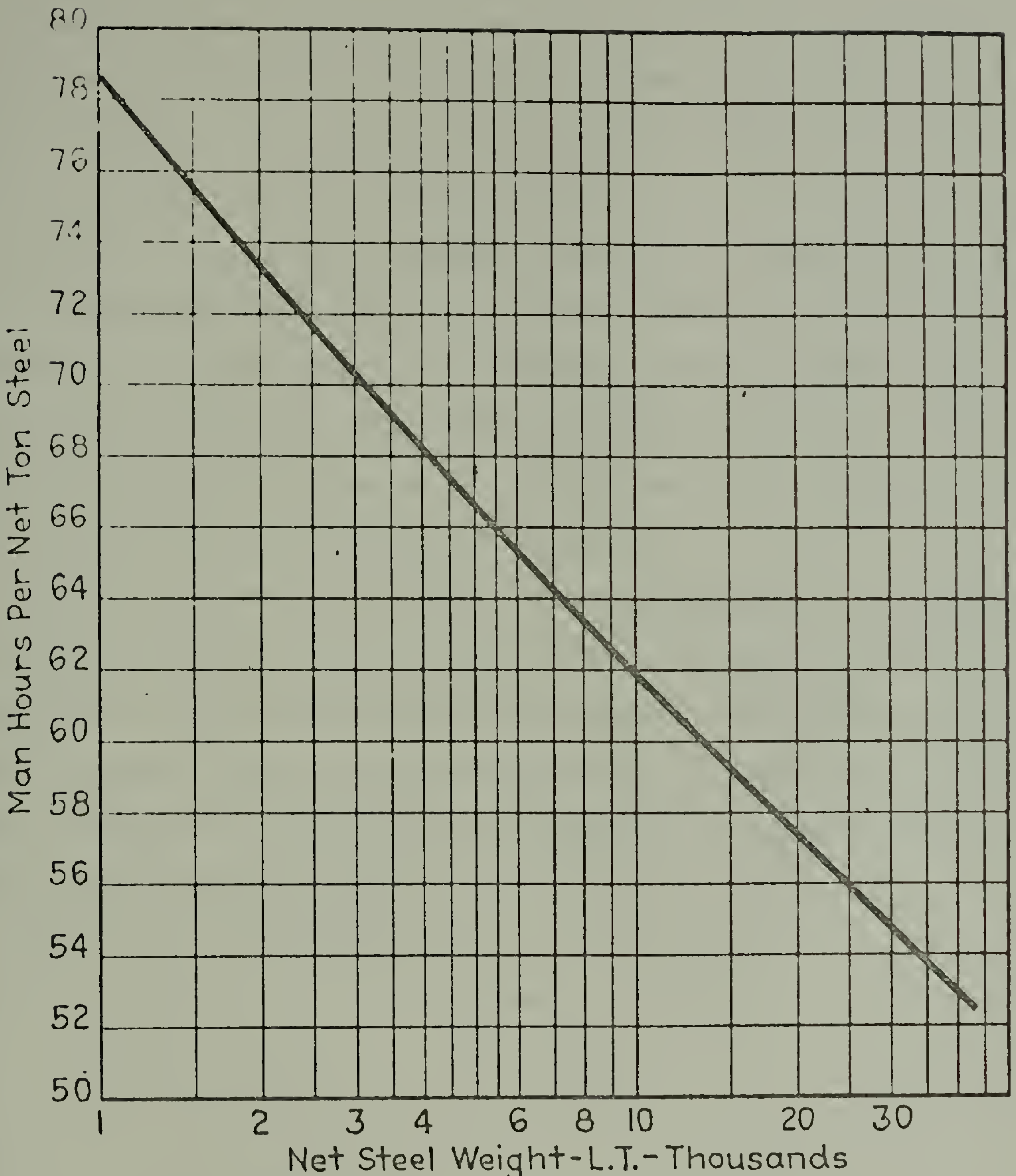


Figure D.8 MAN-HOURS PER NET TON OF STEEL [24]

APPENDIX E. - SUPPORT EQUIPMENT COST [8, 22, etc.]

Support equipment includes all machinery and electrical equipment not included in the propulsion system. Support equipment for a tanker ship, container ship, dry cargo ship, etc. will be quite different and, moreover, their costs will most likely be quite different.

However, for power plant comparison which assumes a common mission and similar support equipment loads only the cost of support equipment energy converters will be considered. For steam power plants the normal support system source of energy is steam from the propulsion system boiler. Diesel and gas turbine plants may use steam, diesel or gas turbine auxiliary systems to generate power for the support systems.

In the case of the steam plant the support equipment cost is neglected for preliminary analysis since the boiler cost is included with that of the power plant. For the diesel and gas turbine plants a cost penalty for the support equipment prime mover or auxiliary boiler is estimated to be $120,000. This estimated cost is based on several reports and is representative for plants of about 20,000 to 30,000 SHP.

The support equipment costs are:

Steam Plant	-	no cost
Diesel Plant ($)	-	0.12 million
Gas Turbine ($)	-	0.12 million

APPENDIX F. - MAINTENANCE AND REPAIR COST

The maintenance and repair cost is calculated using the \$/SHP-year data from Figure F.1. The average maintenance and repair cost data is based on various sources adjusted to 1970 U.S. dollars using information regarding cost and man-hours from reference [29]. It may be seen that steam plants are the least expensive to maintain and repair while diesel plants are the most expensive.

Sample maintenance and repair cost calculation:

- Given: 26,000 SHP Steam Plant
- From Figure F.1 (\$/SHP-year) is 1.8

$$\frac{\$1.8}{\text{SHP}} \times 26{,}000 \text{ SHP} = \$46{,}800.00$$

- Maintenance and repair cost = 0.047 million

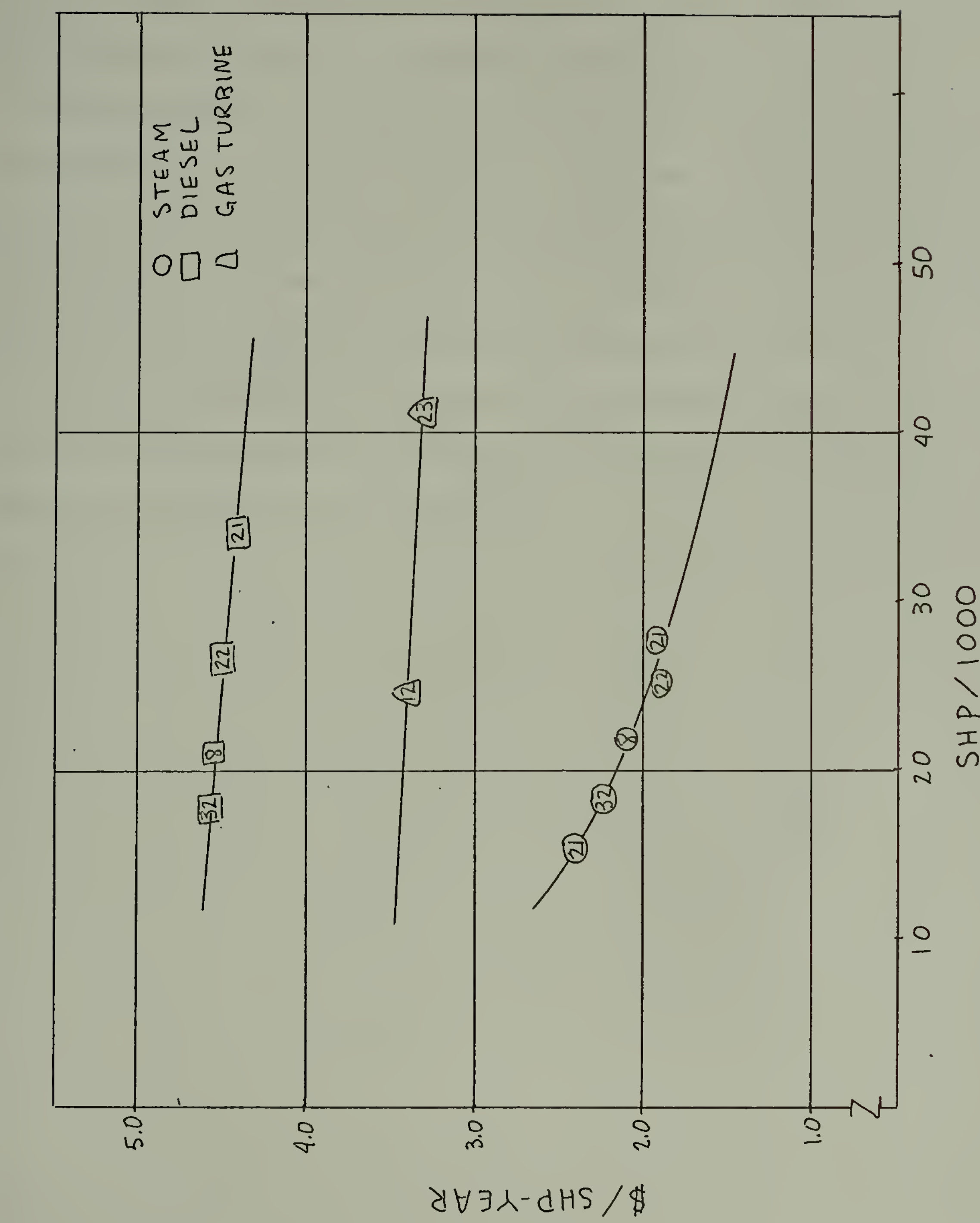


Figure F.1 MAINTENANCE AND REPAIR COSTS FOR VARIOUS POWER PLANT TYPES

APPENDIX G. MANNING COST [8, 19, 31 etc.]

The manning cost will be a function of the number of men and their qualifications necessary to operate the power plant.

Modern trends in propulsion plant design is toward automation to allow reduction of the engineering crews. There are still international rules, U. S. Coast Guard Regulations and Union Regulations which influence the manning. It is conjecture, but it will probably be several more years before automation significantly allows engineering crew reduction.

Using information from references [8] and [19]the manning requirements for the sample manning cost calculation were developed. Figure G.1 is a summary of the manning cost calculation.

MANNING FOR 26,000 SHP COMMERCIAL SHIP

	Steam Plant		Diesel Plant		Gas Turbine Plant	
	No.	$/Year	No.	$/Year	No.	$/Year
Chief Engineer	1	16,970	1	16,970	1	16,970
1st. Asst. Engr.	1	11,500	1	11,500	1	11,500
2nd. Asst. Engr.	1	9,170	1	9,170	1	9,170
3rd. Asst. Engr.	1	8,540	1	8,540	1	8,540
Electrician	1	6,910	1	6,910	2	13,820
Diesel Machinist	-	--	2	14,750	-	--
Pumpman	1	6,760	2	13,520	1	6,760
Oiler	3	15,100	3	16,180	3	16,180
Wiper	3	14,990	3	14,960	-	--
Total	12 men	84,940	15	112,500	10	62,940
Add 58.2% to Base Wage for Overtime & Benefits		134,000		178,000		99,500
Add 34% for Inflation		179,500		242,000		133,000
Manning Cost ($/Year)		0.180 million		0.242 million		0.133 million

FIGURE G.1 SAMPLE MANNING COST CALCULATION SUMMARY

G.1 MANNING COST DATA [31]

Manning Factors

Listed on the following pages are the base pay rates and other information for civil marine personnel. The list is comprehensive so that Definition Contractors may propose the optimum crew for their ship design.

MSTS has developed an experience factor of 58.2% of base pay, which covers overtime, penalty time, other premium payments, and fringe benefits for civil marine personnel. This factor is composed of 33.4% for overtime and penalty time and 24.8% for other payments and benefits. Page XIV 5 thru 7 contain information which is included in the 33.4% part of the 58.2% factor. Contractors may make use of this information in preparing their estimates instead of the 33.4% factor. In addition to base rates and these premium payments and benefits, estimates should include the repatriation and subsistance costs which would be incurred.

Repatriation is required only for those personnel who do not return to CONUS within one year period. Repatriation for personnel outside of CONUS for one year would be the cost of round trip air fare from the forward area of deployment to San Francisco. Under MODES 1 and 3 ships presumably would be outside CONUS in excess of 1 year. The round trip air fare Tokyo to San Francisco is $490 and Okinawa to San Francisco is $394. For repatriation purposes, Hawaii is not considered to be part of CONUS. The round trip air fare between Hawaii and San Francisco is $168..

For ships in other MODES, presumably it would be unnecessary to repatriate the entire crew. In this instance only an amount of .4% of annual civil marine manning costs per ship would be needed for emergency repatriation such as in the case of sickness of death.

Subsistence costs should be computed on the basis of $1.77 per man per day for men based in CONUS. $2.00 per man per day overseas. The difference covers the cost of transportation of provisions overseas.

Dayworkers:

Boatswain (Fgtr.)	$8,526
Carpenter	7,866
Boatswain's Mate (Fgtr.)	6,807
Carpenter's Mate	6,414
Storekeeper (Deck)	6,086
Yeoman (Deck)	6,086
Yeoman-Storekeeper (Deck)	6,086
Able Seaman Maintenance	6,414
Ordinary Seaman (Day)	4,986

Engine Dept. (Officer)

Chief Engineer	$16,973
1st Asst. Engineer	11,502
2nd Asst. Engineer (Day)	9,171
2nd Asst. Engineer	9,171
3rd Asst. Engineer	8,542
Lic. Jr. Engineer	7,932
Engine Cadet	1,334

Engine Dept. (Nonofficer)

Dayworkers:

Chief Electrician	$9,570
2nd Electrician (Day)	7,890
3rd Electrician (Day)	7,530
Chief Electrician (P-2 Turboelectric)	9,984
2nd Electrician (Day) (P-2 Turboelectric)	8,502
3rd Electrician (Day) (P-2 Turboelectric)	8,148
Refr. Engineer (Air Conditioned Transport)	7,860
Electrician - Maintenance	6,912
Refr. Engineer (Day Work)	7,620
Deck Engineer	6,450
Deck Engineer - Machinist	7,374
Unlicensed Jr. Engineer (Day)	6,762
Student Observer (Unlicensed Jr. Engineer)	6,534
Plumber - Machinist	7,374
Plumber	6,912
Asst. Plumber	6,345
Machinist	7,374
Pumpman	6,758
Wiper	4,986
Engine Utilityman	6,450
Storekeeper (Engine)	6,086
Yeoman (Engine)	6,086

Engine Dept. (Nonofficer)

Dayworkers (Cont.)

Yeoman-Storekeeper (Engine)	$6,086

Watchstanders:

2nd Electrician (Watch) (P-2 Turboelectric)	7,212
3rd Electrician (Watch) (P-2 Turboelectric)	6,858
Jr. 3rd Electrician (Watch) (P-2 Turboelectric)	6,636
2nd Electrician (Watch)	6,800
3rd Electrician (Watch)	6,447
Jr. 3rd Electrician (Watch)	6,204
2nd Refr. Engineer (Air Conditioned Transport)	6,618
3rd Refr. Engineer (Air Conditioned Transport)	6,1[illegible]2
Refr. Engineer (Passenger and Dry Cargo)	6,564
2nd Refr. Engineer (Passenger and Dry Cargo)	5,970
3rd Refr. Engineer (Passenger and Dry Cargo)	5,832
Unlicensed Junior Engineer (Watch)	5,604
Refr. Oiler	5,034
Oiler	5,034
Oiler (Diesel)	5,394
Watertender	5,034
Fireman (Oil)	5,034
Fireman - Watertender	5,034
Evaporator - Utilityman	5,394

for ratings carrying base pay rates of $6,475 or more per annum, and for the rating of Assistant Cook (Fgtr.), Fourth Cook. Yeoman, Storekeeper, and Yeoman-Storekeeper, overtime is $3.25 per hour

B. Cargo Rates

for nonofficer ratings in the Deck Department, cargo rates are	$2.46 per hour straight time $4.05 per hour overtime

I. RELIEF OFFICER RATES

A. Relief Deck Officer

regular compensation	$4.33 per hour

B. Relief Engineer

regular compensation	$4.23 per hour

PREMIUM PAY RATES

A. Overtime and Penalty Time

1. Deck Department officer ratings (excluding Radio Officer ratings)

   Overtime rate is $4.33 per hour
   Penalty time rate is $2.86 per hour

2. Radio officer ratings

   Overtime rate is $4.23 per hour
   Penalty time rate is $3.50 per hour

3. Engine Department officer ratings

   Overtime rate is $4.23 per hour
   Penalty time rate is $1.23 per hour

4. Purser Department officer ratings

   Overtime rate is $4.23 per hour
   Penalty time rate is $2.80 per hour

5. Medical Department - Nurse (special project)

   Overtime rate is $3.89 per hour
   Penalty time rate is $2.85 per hour

6. Deck Department nonofficer ratings

   for all ratings except Ordinary Seaman-------------------$ 3.25 per hour
   for Ordinary Seaman--$ 2.46 per hour

7. Engine Department nonofficer ratings

   Overtime rate is $3.25 per hour
   Penalty time rate is $2.09 per hour

8. All ratings of the Steward Department (excluding Chief Steward, Class A-3 and P2-S1-DN3 type ships) and for nonofficer ratings of the Purser Department

   for ratings carrying base pay rates of less than $6,475 per annum, excluding the rating of Assistant Cook (Fgtr.) Fourth Cook. Yeoman, Storekeeper, and Yeoman-Storekeeper, overtime rate is $2.46 per hour

Notes

(a) Each licensed deck officer, including the Master, who does not stand a regular watch and whose normal hours of work at sea are 40 hours per week shall be paid an additional $142.54 per month effective 16 June 1966.

This is applicable only when actually assigned aboard on active status ship including periods of normal shipyard repairs and/or annual overhaul between regularly scheduled voyages. It does not include periods of activation, deactivation, major repairs or alterations. (See CMPI 512.4-5c)*

Any nonwatchstanding licensed deck officer, excluding the Master, who during the course of a voyage is required to stand regular watches will receive penalty time for sea watches stood on Saturdays and Sundays and overtime for such watches stood on holidays. This will be in addition to the nonwatchstanding compensation.

(b) Each licensed engineer, including the Chief Engineer, who does not stand a regular watch and whose normal hours of work at sea are 40 hours per week shall be paid an additional $210.00 per month effective 16 June 1966.

This is applicable only when assigned aboard an active status ship including periods of normal shipyard repairs and/or annual overhaul between regularly scheduled voyages. It does not include periods of activation, deactivation, major repairs or alterations. (See CMPI 512.4-5c)*

Any nonwatchstanding licensed assistant engineer who during the course of a voyage is required to stand regular watches will receive penalty time for sea watches stood on Saturdays and Sundays and overtime for such watches stood on holidays. This will be in addition to the nonwatchstanding compensation.

(c) When any nonofficer personnel of the Engine Department in the rating of Fireman (Oil), Watertender, Fireman-Watertender, Evaporator-Utilityman, Oiler, Oiler (Diesel), Refrigeration Oiler, Unlicensed Junior Engineer (watch), any watch electrician rating, or any watch refrigeration engineer rating is assigned to day work at sea or in port without change in rating title; he shall be paid additional compensation at the rate of $60.00 per month during the period of such assignment to day work.

(d) For the performance of daily auto alarm tests at sea and daily radio station tests at sea, the radio officer on all ships carrying one radio officer shall receive $24.00 per month. On ships where more than one radio officer is employed, each radio officer shall receive $13.00 per month. These amounts are payable during the entire period of assignment, including in-port periods, and are in lieu of any other additional compensation regardless of whether the work is in excess of eight hours or outside the normal spread of hours.

(e) For computing the amount due for a fraction of a month, the monthly additional compensations provided in footnotes (a), (b), (c), and (d) above shall be prorated on the basis of a 30-day month, and, for a full pay period or a fraction of a pay period, they are computed in the same manner as base pay [illegible]ing any fraction of a day as a whole day.

APPENDIX H. - OUTAGE COST [15, 21, 35, 36, 37, 38, etc.]

Outage is related to the reliability, maintainability and availability of the various power plants. A gross quantitative outage cost is the result of multiplying the days a ship loses each year, owing to power plant failures and casualties, by the cost penalty per day. For large tankers and container ships this cost penalty may range from $25,000 to $50,000 per day.

The gross quantitative outage cost is then only related to the reverse of outage and that is availability. Availability factors appear in the literature in various forms. Availability is related to trip time and age of power plant as well as power plant type and horsepower rating.

The following availability factors are developed from references [15], [21], [35], [36], and [37]. They are for preliminary analysis and show trends as exhibited in reference [38]. The availability factors are considered representative for 4,000- to 10,000-mile trips. No consideration has been given to power plant horsepower rating or age.

Power Plant Type	Availability Per Year
Steam	0.992
Slow-speed Diesel	0.988
Medium-speed Diesel	0.945
Gas Turbine	0.983

Calculate outage cost for 26,000 SHP steam plant, assume $40,000 per day penalty:

- Given: Steam Plant
- Given: Penalty cost (day) is 40,000.00

  Availability Factor is 0.992

365 days - (0.992) 365 = 2.92 days delay per year

$$\frac{\$40,000}{\text{day}} \times 2.92 \text{ days} = \$117,000$$

- Outage cost (\$) = .117 million

APPENDIX I. - FUEL COST

Calculation of fuel cost for a specific ship mission will depend upon SHP, hours of operation of power plant, type of power plant, fuel rate (lbs. fuel/SHP hr.) and may vary over considerable cost range. Using fuel rate determined from Figures I.1 and I.2 and cost data from Appendix I.2 and conversion factors from Appendix I.1, a fuel cost calculation for various 26,000 SHP power plants operating for 6800 hrs./yr. is summarized in the table below. The table shows how fuel cost may vary over a considerable cost range.

FUEL COST SUMMARY TABLE

SHP - 26,000 for 16.0 KT COMMERCIAL SHIP 82 RPM

HOURS OF OPERATION PER YEAR - 6800 hrs.

	Steam	Slow-Speed Diesel	Aircraft Gas Turbine
SHP:	26,000	27,400***	26,000
Fuel Rate (SFC):	.440	.355	.460
Op. Hours/Yr.:	6800	6800	6800
Fuel Cost ($/bbl.):	3.45*	3.45*	5.01**
Fuel Cost ($/lb.):	0.0105	0.0105	0.0169
Total Fuel Cost ($):	0.817 million	0.695 million	1.375 million

* Bunker "C" East Coast

** Marine Diesel East Coast

*** Corrected to 100 RPM

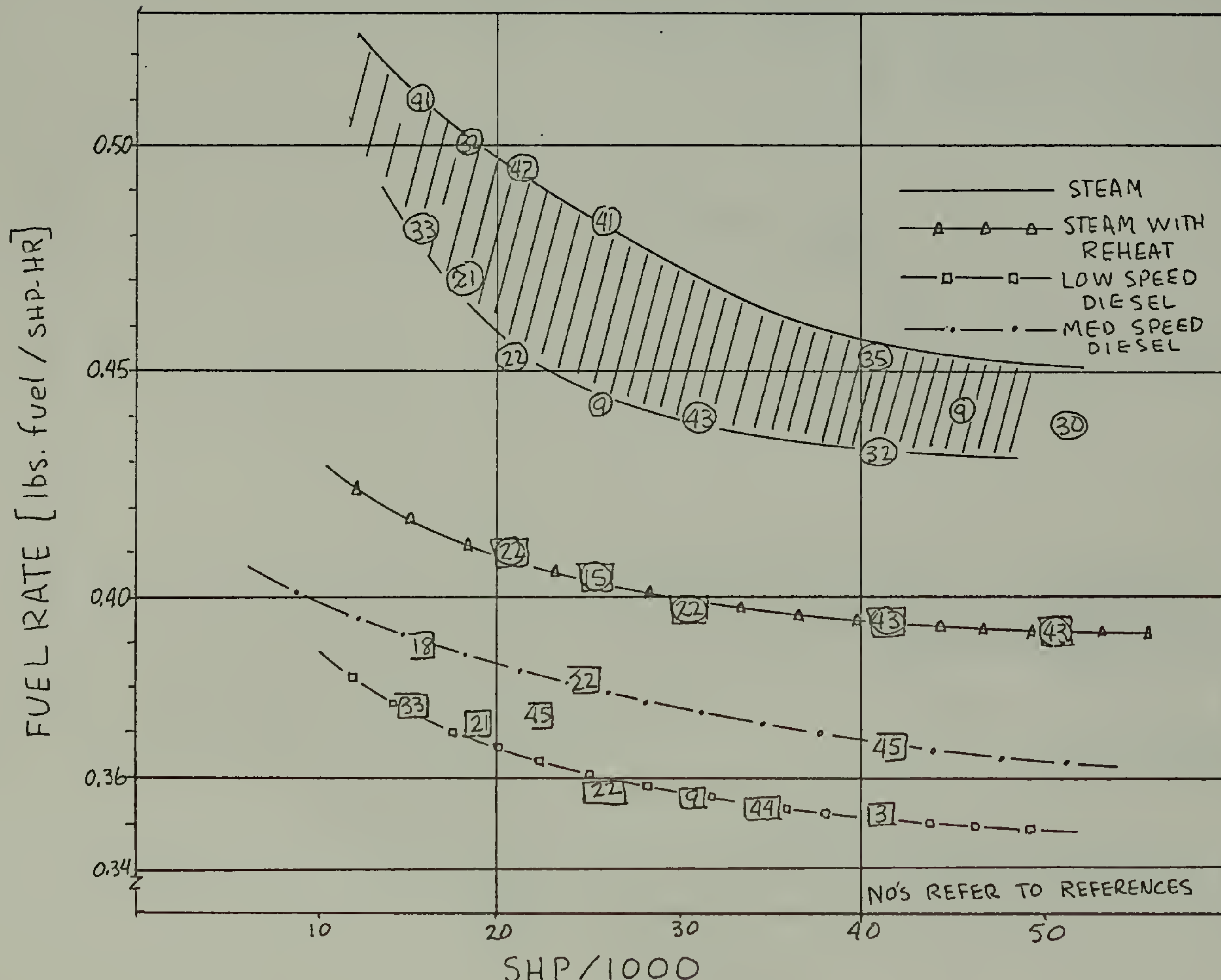


Figure I.1 FUEL RATE STEAM AND DIESEL POWER PLANTS

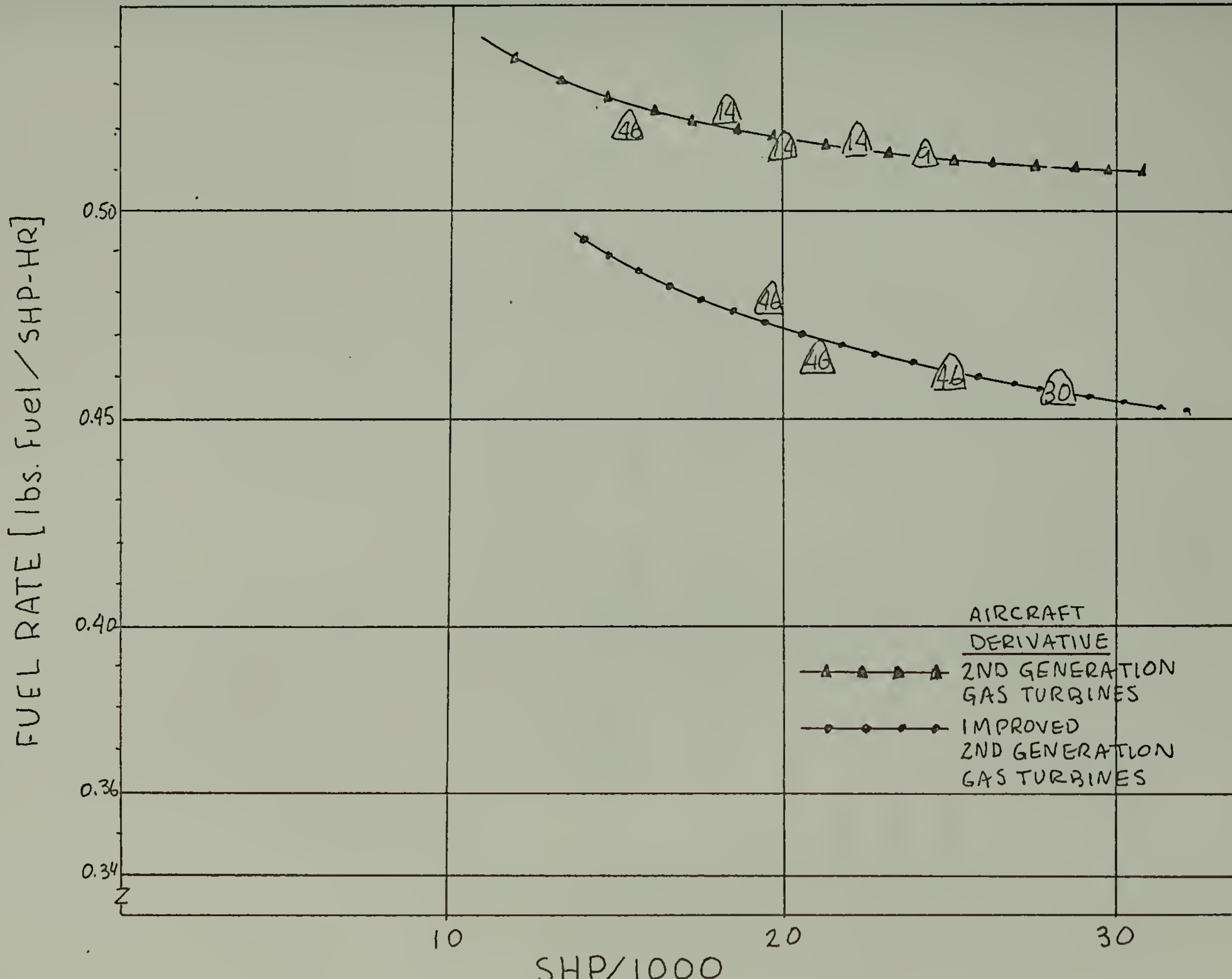


Figure I.2 FUEL RATE GAS TURBINE POWER PLANTS

I.1 Conversion Factors

- 1 Cubic Foot (ft^3) = 7.48 gallons (gals)
- 1 Barrel (bbl) = 42.0 gals.
- 1 Ton = 2240 lbs.
- 1 Ton = 38.0 ft^3 Bunker C
- 1 Ton = 42.3 ft^3 Diesel Marine
- 1 Ton = 41.3 ft^3 Navy Distillate
- 1 Ton = 44.1 ft^3 Navy JP-5

Example calculation of fuel cost per pound for Bunker "C."

- $\frac{\$3.45}{\text{bbl}} \times \frac{1 \text{ bbl}}{42.0 \text{ gal}} \times \frac{7.48 \text{ gal}}{ft^3} \times \frac{38.0 \ ft^3}{\text{ton}} \times \frac{\text{ton}}{2240 \text{ lbs}} = 1.05 \times 10^{-2} \frac{\$}{\text{lb}}$

- Cost Bunker "C" (\$/lbs.) = 0.0105

I.2 FUEL COSTS [39, 40, 47]

Fuel Type	[39] Dec '71 EAST COAST	[39] Dec '71 WEST COAST	[40] Nov '70 EAST COAST	[40] Nov '70 WEST COAST	[47] Oct '71 EAST COAST	[47] Oct '71 WEST COAST
Bunker "C" ($/bbl)	3.20	3.89	--	3.70	3.45	4.14
Marine Diesel ($/bbl)	4.56	5.16	--	5.79	5.01	5.41

APPENDIX J. - LUBE OIL COST

Lube oil cost calculation will depend upon SHP, lube oil cost per unit of issue, power plant type, hours of operation and lube oil consumption. In the preliminary analysis oil cost for steam and gas turbine power plants is negligible and therefore it is disregarded. Only the diesel lube oil cost calculation is necessary.

Sample Lube Oil Cost Calculation for slow-speed diesel assuming 6800 hr./yr. operation at 27,400 SHP is:

- Given: low-speed diesel, 27,400 SHP
- Given: Operation (hr./yr.) = 6800
- From Appendix J.1 crankcase lube oil ($/gal.) is 1.03 and diesel cylinder oil ($/gal.) is 1.68
- From Appendix J.2 crankcase oil consumption $\frac{\text{gal}}{(\text{SHP}/1000)\text{hr}}$ is 0.043 and cylinder oil consumption $\frac{\text{gal}}{(\text{SHP}/1000)\text{hr}}$ is 0.111

  Lube Oil Cost ($/yr.) = 8,250 + 34,800
- Lube Oil Cost ($/yr.) = .043 million

J.1 LUBE OIL COST DATA [22, 29, etc.]

TYPE OF OIL	$/GALLON
Diesel Reduction Gear Oil:	1.16
Diesel Crankcase (Slow speed diesel):	1.03
Diesel Cylinder (Slow speed diesel):	1.68
Diesel (Medium Speed Diesel):	1.31

J.2 LUBE OIL CONSUMPTION RATE [22]

	$\frac{\text{GRAMS}}{\text{SHP (Metric)-hr}}$	$\frac{\text{gal}}{\text{(SHP/1000)-hr}}$
Slow-Speed Diesel Crankcase Oil	0.20	0.043
Slow-speed Diesel Cylinder Oil	0.40	0.111
Medium-Speed Diesel Lube Oil	1.20	0.330
Medium-Speed Diesel Gear Oil	negligible	negligible

APPENDIX K. - SUPPORT EQUIPMENT OPERATING COST

Since the selection problem involves a common mission ship the support equipment will have similar functions and loads. Although the power plants may have different support systems the cost of their operation is assumed similar and for preliminary analysis is neglected.

For certain ship missions the support equipment may play a significant role in the power plant selection problem. For those missions a more detailed support equipment analysis will be required and the result included in the preliminary analysis.

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Ship power plant
selection.

DISPLAY

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